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Identification of the Radionuclides in Spent Nuclear Fuel that may be Detected by Compton Suppression and Gamma-Gamma Coincidence Methods

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Identification of the Radionuclides in Spent Nuclear Fuel that may be Detected by Compton Suppression and Gamma-Gamma Coincidence Methods

by

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Report

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Abstract

Identification of the Radionuclides in Spent Nuclear Fuel that may be Detected by Compton Suppression and Gamma-Gamma Coincidence Methods

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The University of Texas at Austin, 2011

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The nuclides present in spent nuclear fuel are categorized according to their capacity for detection by Compton suppression or gamma-gamma coincidence methods. The fifty nuclides with the highest activities in spent fuel are identified, their decay schemes analyzed, and the best detection scheme for each is recommended.

Table of Contents

List of Tables

List of Figures

Background

The International Atomic Energy Agency (IAEA) was founded by the United Nations in 1957 with the stated objective of seeking "…to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world."[1] Among the numerous functions prescribed by the Statute of the IAEA is the authorization "to establish and administer safeguards designed to ensure that special fissionable and other materials…are not used in such a way as to further any military purpose…"[1]

In carrying out this function, the IAEA must utilize all available means to detect and identify the diversion of special nuclear material in the facilities that the IAEA oversees. Among the tools and methods available to IAEA inspectors are detectors capable of identifying the spectra and specific gamma rays emitted by radioactive materials.[2]

In an attempt to further expand the tools available to monitor the processing of special nuclear material (SNM), Pacific Northwest National Laboratory (PNNL) is developing the Multi-Isotope Process (MIP) Monitor.[3,4] The MIP Monitor is designed to collect the gamma ray signatures emitted from radioactive solutions in-process at recycling facilities, while simultaneously analyzing the signatures through pattern recognition and other multivariate analysis methods to detect off-normal conditions. Any

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[1] International Atomic Energy Agency, "Statute of the IAEA," http://www.iaea.org/About/statute_text.html.
[2] International Atomic Energy Agency, "Tools for Nuclear Inspection," 2004. http://www.iaea.org/Publications/Factsheets/English/inspectors.pdf.
[3] C.R. Orton, "The Multi-Isotope Process Monitor: Non-destructive, Near-Real-Time Nuclear Safeguards Monitoring at a Reprocessing Facility," Dissertation, The Ohio State University, 2009.
[4] C.R. Orton, et al., "Proof of Concept Simulations of the Multi-Isotope Process Monitor: An Online, Nondestructive, Near-Real-Time Safeguards Monitor for Nuclear Fuel Reprocessing Facilities," Nucl. Instr. and Methods in Phys Research A, 629(1):209-219.

off-normal conditions could indicate the possible diversion of nuclear material from the process streams.

METHODS OF DETECTION

In order to accomplish the task of detecting the diversion of nuclear materials, the MIP Monitor relies on advanced gamma radiation detection and analysis techniques. To further improve the detection capabilities of the MIP monitor, future versions of the system may incorporate both Compton suppression (anti-coincidence) and gamma-gamma (coincidence) detection methods.

Compton Suppression (Anti-Coincidence)[5,6]

Gamma radiation detectors often consist of a gamma absorbing material (generally a crystal) that converts the energy of incident gamma rays to light or electrical pulses. Gamma rays that enter the crystal may interact by photoelectric absorption, pair production, or Compton scattering. The gamma's kinetic energy is measured by the intensity of the light or electrical pulse produced by the detector.[7,8]

Ideally, incident gammas deposit all of their kinetic energy into the detector crystal. When full-energy absorption occurs, the gamma's energy is accurately measured. However, when a gamma undergoes one or more scattering events, it may escape from the detector after depositing only a portion of its initial energy. In this case, the detector will record only the fraction of the gamma's energy that was deposited prior to escaping.

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[5] S. Landsberger, "Compton Suppression Neutron Activiation Analysis Methods in Environmental Analysis," J. Radioanal. Nucl. Chem. 179 (1994) 67-79.
[6] S. Landsberger and S. Peshev, "Compton Suppression Neutron Activation Analysis: Past, Present and Future," J. Radioanal. Nucl. Chem. 202 (1996) 201-224.
[7] H. Cember and T.E. Johnson, *Introduction to Health Physics*, 4th ed., McGraw-Hill Companies, 2009.
[8] G.F. Knoll, *Radiation Detection and Measurement*, 2nd Edition, John Wiley and Sons, 1989.

The gamma energy spectrum that is recorded by a radiation detector will reflect both the desired full-energy peaks, as well as a continuum of lower energy detections due to escaped gammas. This "Compton continuum" is illustrated in Figure 1 for the detected gamma spectrum of ^{137}Cs. In cases where multiple gamma energies may be present, the Compton continuum that results from the higher energy gammas may be so large that lower energy gammas are masked and cannot be resolved from the Compton continuum.

To reduce the likelihood that detected events result from gammas that partially deposit in the detector, a Compton suppression system may be used. In Compton suppression, one or more secondary detectors are installed surrounding a primary detector. When both the primary and secondary detectors sense a pulse simultaneously (within a fixed coincidence timescale), it is likely that the pulses resulted from a gamma that underwent one or more Compton scattering events before escaping the primary detector. These simultaneous pulses may then be electronically rejected, such that the counts resulting from these events do not enter into the measured spectrum. The pulses that are not rejected are therefore more likely to have resulted from full-energy absorptions in the primary detector.

For radiation decay events that result in the production of a single gamma ray, Compton suppression is an ideal detection method, due to its ability to reject the signals that result from Compton scattering and subsequent escapes. However, for decay events that result in multiple coincident gamma rays, Compton suppression systems may reject even full-energy absorption events, as each of the coincident gammas may result in simultaneous pulses in the primary and secondary detectors.

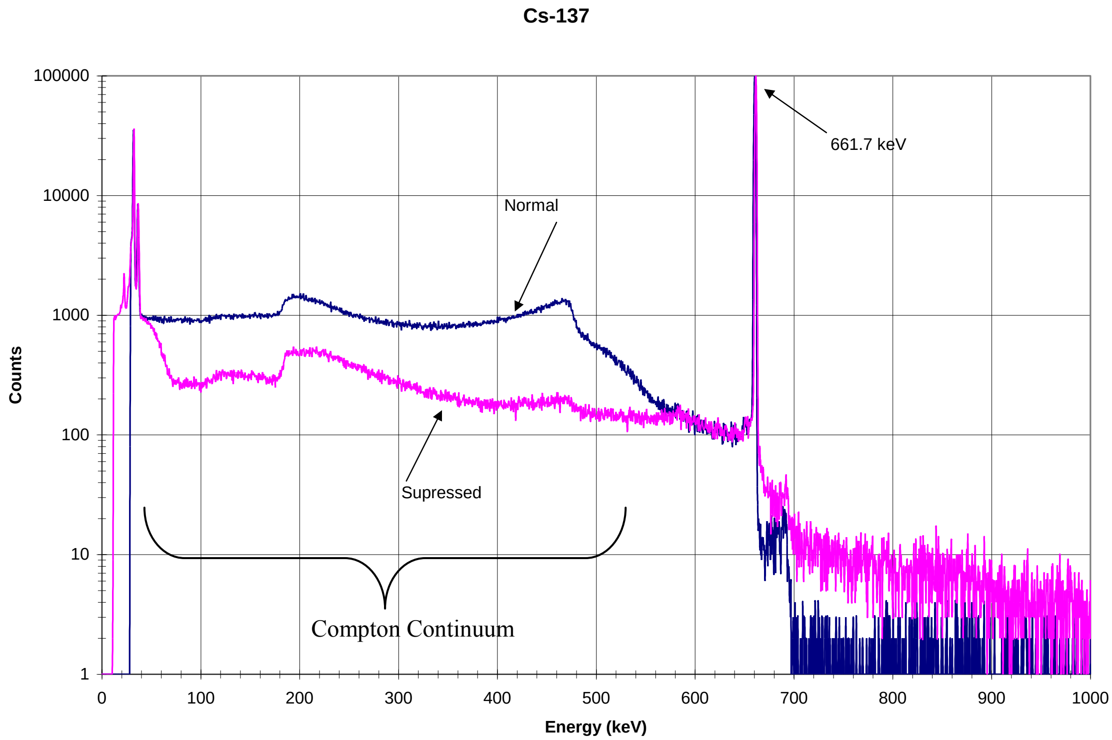

Figure 1: Measured gamma spectrum of ^{137}Cs.[9] The dark purple data is the measured spectrum using a normal gamma detector. The pink data is the measured spectrum using a Compton suppression system. In both cases, the peak at 661.7 keV indicates full-energy absorption of the ^{137}Cs primary gamma rays. The Compton continuum of energy detections below the full-energy peak results when gammas undergo one or more Compton scattering events before escaping the detector. Compton suppression decreases the magnitude of this Compton continuum, allowing lower energy gammas to be more easily resolved.

Additionally, Compton suppression systems may not be effective for characterizing the spectra of radioactive samples with high activities or complex spectra. In these cases the high activities or complex spectra increase the likelihood that full-energy events will be rejected, because many absorptions may occur in both the primary and secondary detectors within the coincidence timescale.[8]

[9] University of Texas - Austin, Nuclear Engineering Teaching Laboratory.

To improve the detector efficiency in these cases, energy gating may be implemented. In energy gating, any detector interactions that occur outside of a defined energy window are rejected. Because a sample of spent fuel may contain dozens of different nuclides each producing gamma rays, energy gating focuses the detection on only those gamma energies of interest.[10]

Gamma-Gamma Coincidence

In contrast to anti-coincidence detection schemes, coincidence detection methods rely on the cascading production of multiple gamma rays per disintegration of a radioactive material. Using two primary gamma detectors, a gamma-gamma coincidence system accepts only simultaneous detections, rejecting any single detections.[10] In this way, the coincidence scheme improves the ability to characterize the gamma spectrum from radioactive materials that produce two or more gamma rays simultaneously.

However, gamma-gamma coincidence detection schemes are vulnerable to Compton scattering and partial energy deposition that Compton suppression systems are designed to reduce. If simultaneous gamma rays are not fully absorbed in the detectors, the detected energy spectrum may be inaccurate.

As with Compton suppression systems, gamma-gamma coincidence schemes may not be effective at characterizing the spectra of radioactive samples with high activities or complex spectra. The high activities or complex spectra increase the likelihood that multiple independent gamma absorption events will be detected simultaneously, even though the gamma rays did not originate from the same decay event.

To improve detection efficiency in these cases, energy gating may be implemented to focus the detection on only those gamma energies of interest.

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[10] B.E. Tomlin, et al., "γ γ Coincidence Spectrometer for Instrumental Neutron-Activation Analysis," Nucl. Instr. and Meth. A 589 (2008) 243-249.

ORIGEN

To improve the capabilities of the MIP, this analysis seeks to identify the radionuclides that may be best detected using either Compton suppression or gamma-gamma coincidence methods. ORIGEN-ARP[11] was employed to characterize the nuclides present in spent fuel.

The computational code of ORIGEN-ARP, ORIGEN-S,[12] computes the time-dependent activation, decay, and transmutation of radionuclides in materials for input irradiation and decay periods. ORIGEN-ARP incorporates a user-interface and built-in cross-sections for various commercial Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) fuel types.

In this analysis, nuclides present in both PWR and BWR fuels are considered with an assumed 4% ^{235}U enrichment, a burnup time 45,000 MWd/MTU (megawatt-days per metric ton of Uranium), and an average power during irradiation of 32 MW/MTU. The post-irradiation decay time in each case is three years.

FUEL TYPES CONSIDERED

For PWRs, the nuclide results were compared from Combustion Engineering's 14x14 fuel, Combustion Engineering's 16x16 fuel, and Westinghouse's 17x17 Standard fuel.[11] For BWRs, results were compared from General Electric's 9x9-7 GE11 fuel and AREVA's 9x9-9 Atrium 9 fuel.[11] The cross-sections for each of these fuel types are contained in ORIGEN-ARP.

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[11] Gauld, Bowman, and Horwedel, ORNL/TM-2005/39, "ORIGEN-ARP: Automatic Rapid Processing System for Spent Fuel Depletion, Decay, and Source Term Analysis," Ver. 6, Jan 2009.

[12] Gauld, Hermann, and Westfall, ORNL/TM-2005/30, "ORIGEN-S: Scale System Module to Calculate Fuel Depletion, Actinide Transmutation, Fission Product Buildup and Decay, and Associated Radiation Source Terms," Ver. 6, Jan 2009.

The resulting nuclide lists for each fuel type are nearly identical, with the only substantial differences arising in the relative activities of each of the nuclides. These relative differences in activities will be ignored, as only the presence of each nuclide in spent fuel is being considered for this analysis.

NUCLIDE LIST

The final nuclide list that follows accounts for the fifty nuclides with the highest activities present in spent fuel after a decay period of three years and the input parameters described above. In the calculations for each of the various fuel types, the relative and absolute activities of each nuclide depend on the specific fuel type being considered. However, these differences will be ignored, as only the presence of each nuclide in spent fuel is being considered in this analysis. Beyond the magnitude of the activities of each of the nuclides, the actual listing of nuclides is independent of the specific fuel type. Further, the listing of nuclides is nearly independent of the fuel burnup time for burnups between 20,000 MWd/MTU and 65,000 MWd/MTU.

Table 1 contains the listing of the nuclides to be considered.

Table 1: The fifty nuclides with the highest activities that will be considered herein.

^{137}Cs	^{241}Pu	^{137m}Ba	^{90}Y	^{90}Sr
^{147}Pm	^{144}Pr	^{144}Ce	^{106}Ru	^{106}Rh
^{134}Cs	^{85}Kr	^{154}Eu	^{244}Cm	^{125}Sb
^{238}Pu	^{155}Eu	^{125m}Te	^{144m}Pr	^{241}Am
^{3}H	^{240}Pu	^{242}Cm	^{151}Sm	^{239}Pu
^{110m}Ag	^{239}Np	^{243}Am	^{243}Cm	^{95}Nb
^{99}Tc	^{121m}Sn	^{127m}Te	^{127}Te	^{121}Sn
^{242m}Am	^{242}Am	^{95}Zr	^{152}Eu	^{119m}Sn
^{123}Sn	^{237}U	^{242}Pu	^{110}Ag	^{93}Zr
^{91}Y	^{234}U	^{126m}Sb	^{126}Sn	^{135}Cs

Results

Table 2 contains a summary of the highest intensity gamma ray produced by each nuclide, as well as the recommended detection method for each of the nuclides listed in Table 1.

Table 2: Summary of each nuclide's highest intensity gamma ray, as well as the recommended method of detection.

Nuclide	**Primary Gamma Energy (keV)**	**Absolute Intensity (%)**	**Detection Method**
^{137}Cs	661.657	85.10	A
^{241}Pu	-	-	-
^{137m}Ba	661.657	89.90	A
^{90}Y	-	-	-
^{90}Sr	-	-	-
^{147}Pm	-	-	-
^{144}Pr	696.510	1.342	A
^{144}Ce	133.515	11.09	A
^{106}Ru	-	-	-
^{106}Rh	511.8605	20.4	C
^{134}Cs	604.721	97.62	C
^{85}Kr	-	-	-
^{154}Eu	123.0706	40.4	C
^{244}Cm	-	-	-
^{125}Sb	427.874	29.8	A
^{238}Pu	-	-	-
^{155}Eu	86.5479	30.7	A
^{125m}Te	35.504	6.67	A
^{144m}Pr	-	-	-
^{241}Am	59.5409	35.9	A
^{3}H	-	-	-
^{240}Pu	-	-	-
^{242}Cm	-	-	-
^{151}Sm	-	-	-
^{239}Pu	-	-	-
^{110m}Ag	657.76	94.3	C
^{239}Np	106.123	26.3	C
^{243}Am	74.66	67.2	A

Table 2: (Continued)

Nuclide	Primary Gamma Energy (keV)	Absolute Intensity (%)	Detection Method
^{243}Cm	277.599	14.0	A
^{95}Nb	765.803	99.808	A
^{99}Tc	-	-	-
^{121m}Sn	37.15	1.85	A
^{127m}Te	-	-	-
^{127}Te	-	-	-
^{121}Sn	-	-	-
^{242m}Am	-	-	-
^{242}Am	-	-	-
^{95}Zr	756.725	54.38	A
^{152}Eu	121.7817	28.67	C
^{119m}Sn	23.875	16.5	A
^{123}Sn	-	-	-
^{237}U	59.5409	34.5	C
^{242}Pu	-	-	-
^{110}Ag	657.5	4.50	A
^{93}Zr	-	-	-
^{91}Y	-	-	-
^{234}U	-	-	-
^{126m}Sb	666.1	86	C
^{126}Sn	87.567	37	A
^{135}Cs	-	-	-

A = anti-coincidence (Compton suppression)
C = coincidence (gamma-gamma)
Note: Those nuclides with no gamma energy listed do not produce any gammas with intensities greater than 1%.

The following sections detail the gamma radiation produced by each nuclide, as well as the determination of the recommended detection method for each nuclide. In each case, only those gamma rays with absolute intensities exceeding 1% are considered. Many of the nuclides produce gamma radiation with intensities less than 1%; however, these gammas are not likely to be easily detectable. Additionally, x-rays that may be produced by each of the nuclides have been ignored.

Analysis of Each Nuclide

^{137}Cs

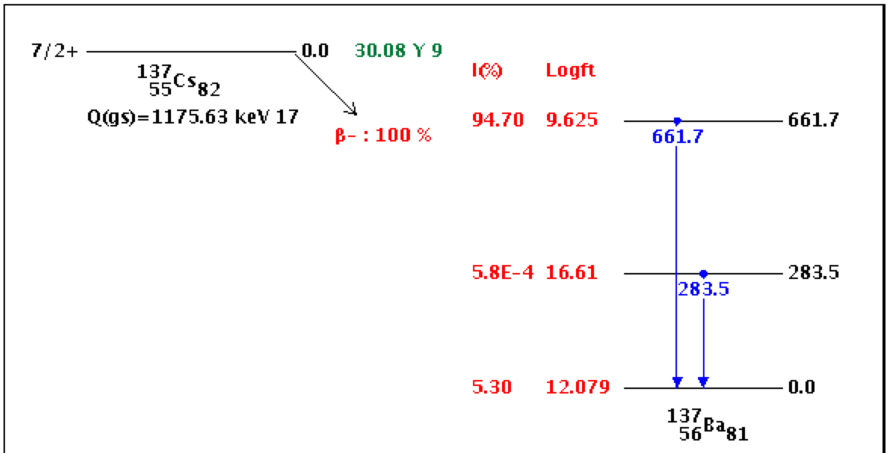

Figure 2: ^{137}Cs decay scheme.[13]

Table 3: ^{137}Cs decay gamma rays (with intensities greater than 1%).[13]

Gamma #	Energy (keV)	Intensity (%)	Coincidences (Gamma #)
1	661.657	85.10	None

^{137}Cs represents the classic nuclide for detection in Compton suppression systems, as the decay of ^{137}Cs produces only one significant gamma ray with a high intensity. This gamma ray is actually the direct result of the decay of ^{137m}Ba, as ^{137}Cs most often decays by beta emission to produce the relatively short-lived (2.55 min half-life) ^{137m}Ba.

[13] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=137CS&unc=nds.

^{241}Pu

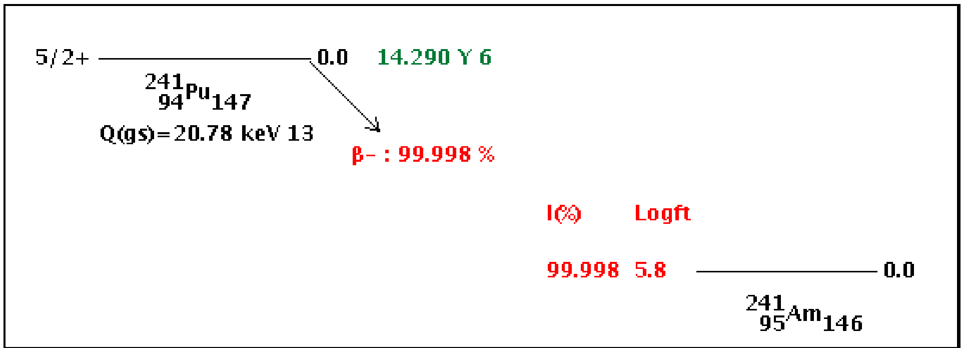

Figure 3: ^{241}Pu decay scheme.[14]

^{241}Pu decays by beta emission, producing no gamma radiation with intensities greater than 1%.

[14] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=241PU&unc=nds.

^{137m}Ba

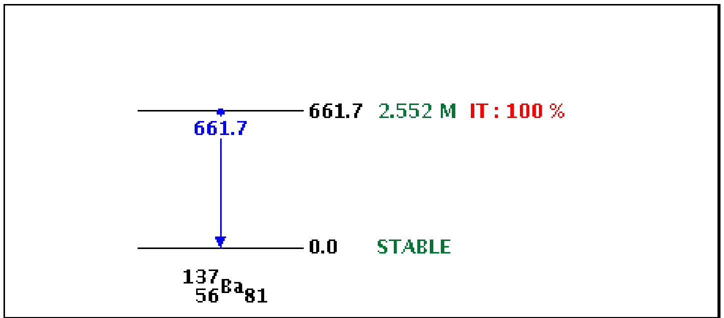

Figure 4: ^{137m}Ba decay scheme.[15]

Table 4: ^{137m}Ba decay gamma rays (with intensities greater than 1%).[15]

Gamma #	Energy (keV)	Intensity (%)	Coincidences (Gamma #)
1	661.657	89.90	None

The metastable state of ^{137}Ba decays to produce one gamma ray with high intensity. This gamma ray is most often attributed to the decay of ^{137}Cs, as the decay of ^{137}Cs produces ^{137m}Ba. Since ^{137m}Ba produces one gamma ray, this gamma is most easily detectable by a Compton suppression system. In practice, it is likely that detection of the gammas produced by ^{137m}Ba will be attributed to the decay of ^{137}Cs.

[15] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=137BA&unc=nds.

^{90}Y

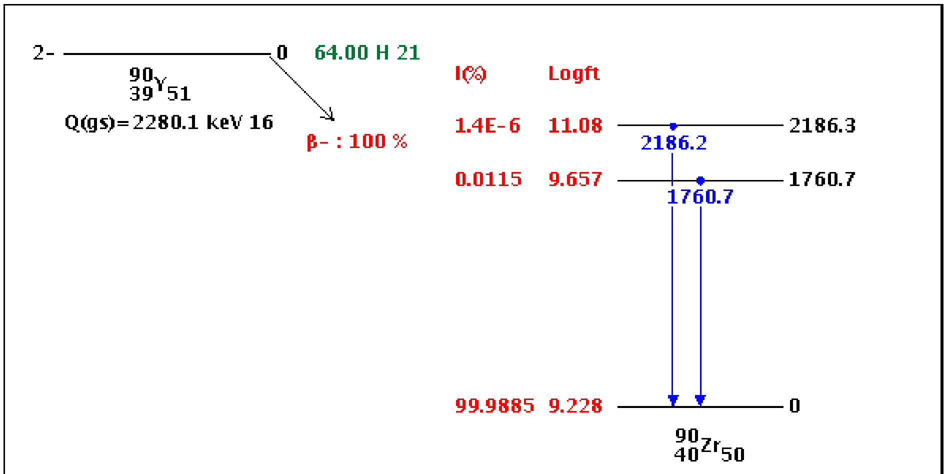

Figure 5: ^{90}Y decay scheme.[16]

^{90}Y decays by beta emission and is capable of producing two gamma rays. However, both of these gammas have intensities less than 1%, as ^{90}Y most often (99.99%) decays directly to the ground state of ^{90}Zr.

[16] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=90Y&unc=nds.

^{90}Sr

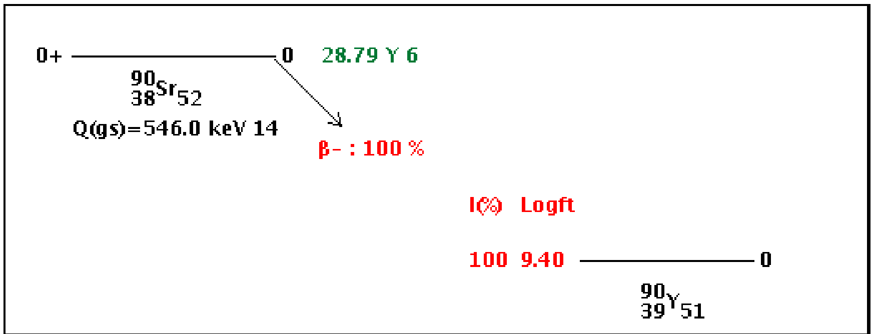

Figure 6: ^{90}Sr decay scheme.[17]

^{90}Sr decays by beta emission, producing no gamma rays.

[17] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=90SR&unc=nds.

^{147}Pm

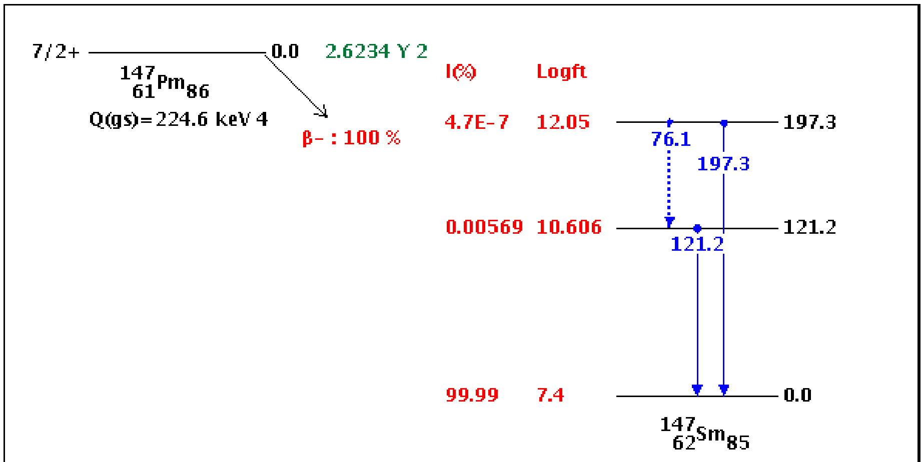

Figure 7: ^{147}Pm decay scheme.[18]

^{147}Pm does not produce any gammas with intensities greater than 1%.

[18] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=147PM&unc=nds.

^{144}Pr

The decay scheme for ^{144}Pr is shown in Appendix 1, Figure 38.

Table 5: ^{144}Pr decay gamma rays (with intensities greater than 1%).[19]

Gamma #	Energy (keV)	Intensity (%)	Coincidences (Gamma #)
1	696.510	1.342	None

^{144}Pr is capable of producing multiple gamma rays. However, only one of these gammas has an intensity greater than 1%. As this gamma does not share significant coincidences, ^{144}Pr may be best detected using a Compton suppression system.

[19] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=144PR&unc=nds.

^{144}Ce

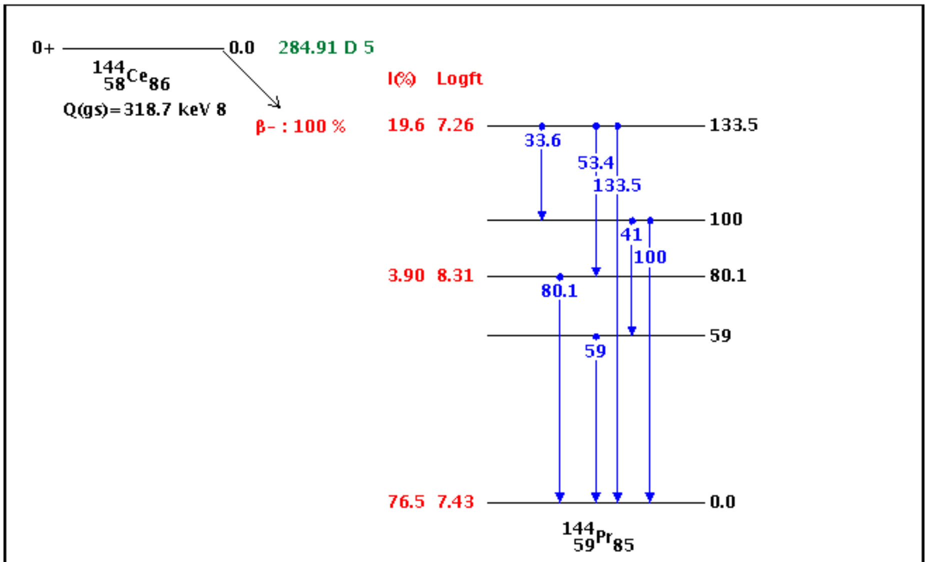

Figure 8: ^{144}Ce decay scheme.[20]

Table 6: ^{144}Ce decay gamma rays (with intensities greater than 1%).[20]

Gamma #	Energy (keV)	Intensity (%)	Coincidences (Gamma #)
1	133.515	11.09	None
2	80.120	1.36	None

^{144}Ce decays to produce two gamma rays with intensities greater than 1%. These gammas are not coincident with each other. Therefore, ^{144}Ce may be best detected using a Compton suppression system.

[20] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=144CE&unc=nds.

^{106}Ru

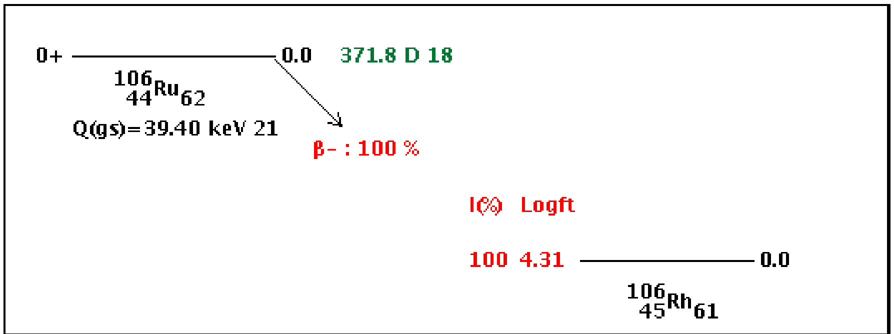

Figure 9: ^{106}Ru decay scheme.[21]

^{106}Ru decays by beta emission, producing no gamma rays.

[21] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=106RU&unc=nds.

^{106}Rh

The decay scheme for ^{106}Rh is shown in Appendix 1, Figure 39.

Table 7: ^{106}Rh decay gamma rays (with intensities greater than 1%).[22]

Gamma #	Energy (keV)	Intensity (%)	Coincidences (Gamma #)
1	511.8605	20.4	2, 3
2	621.93	9.93	1
3	1050.41	1.56	1

^{106}Rh produces more than eighty different gamma rays. Those with the highest intensities have energies of 512 keV and 622 keV and are in coincidence. A gamma-gamma coincidence detection system may be utilized to detect these two high intensity gammas.

Additionally, since these two gammas have intensities that vary by a factor of two, it may be possible to detect ^{106}Rh using a Compton suppression system, detecting the 512 keV gammas that are not in coincidence with other gammas.

[22] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=106RH&unc=nds.

^{134}Cs

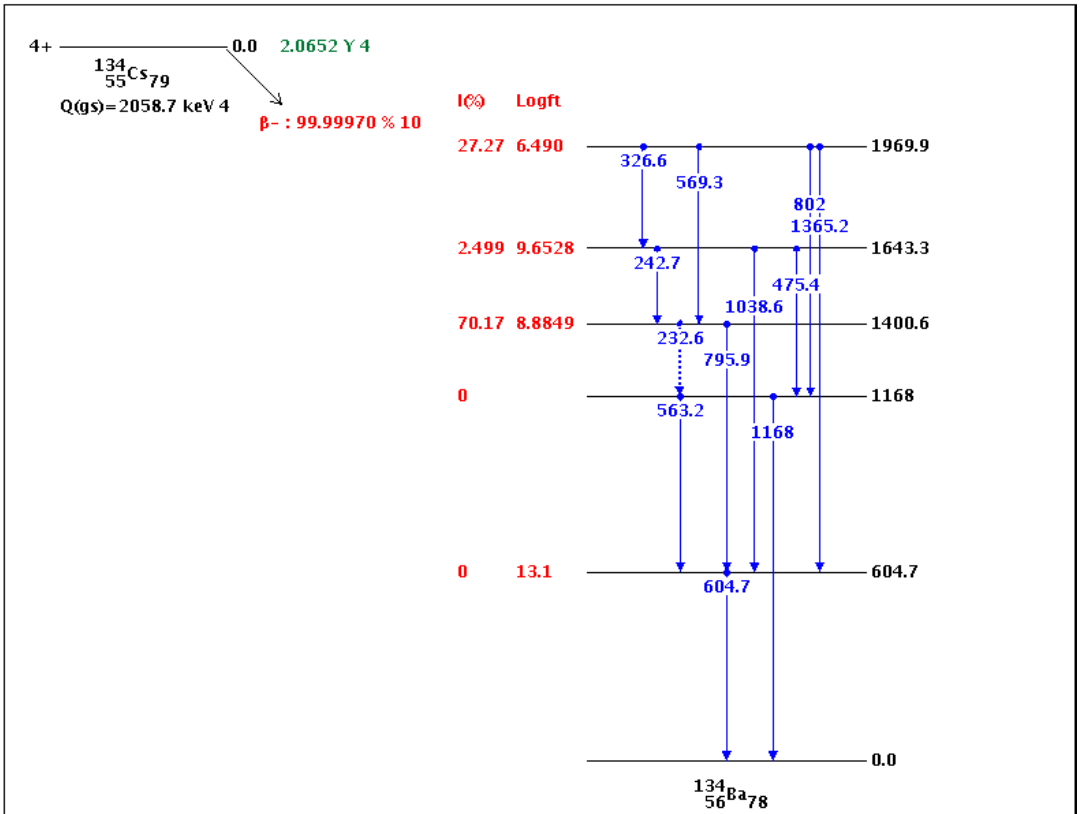

Figure 10: ^{134}Cs decay scheme.[23]

Table 8: ^{134}Cs decay gamma rays (with intensities greater than 1%).[23]

Gamma #	**Energy (keV)**	**Intensity (%)**	**Coincidences (Gamma #)**
1	604.721	97.62	2, 3, 4, 5, 6, 8
2	795.864	85.46	1, 3
3	569.331	15.373	1, 2, 5, 7
4	801.953	8.688	1, 5, 7
5	563.246	8.338	1, 3, 4, 8
6	1365.185	3.017	1
7	1167.968	1.790	3, 4, 8
8	475.365	1.477	1, 5, 7

[23] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=134CS&unc=nds.

^{134}Cs has eight gamma rays with intensities greater than 1%. The most notable are the high intensity gammas at 605 keV and 796 keV. These gammas both have intensities greater than 80%, and they are in coincidence. Therefore, ^{134}Cs is an excellent candidate for detection by gamma-gamma coincidence methods. However, this detection scheme will be complicated by the numerous other coincidences that occur with relatively high intensities.

^{85}Kr

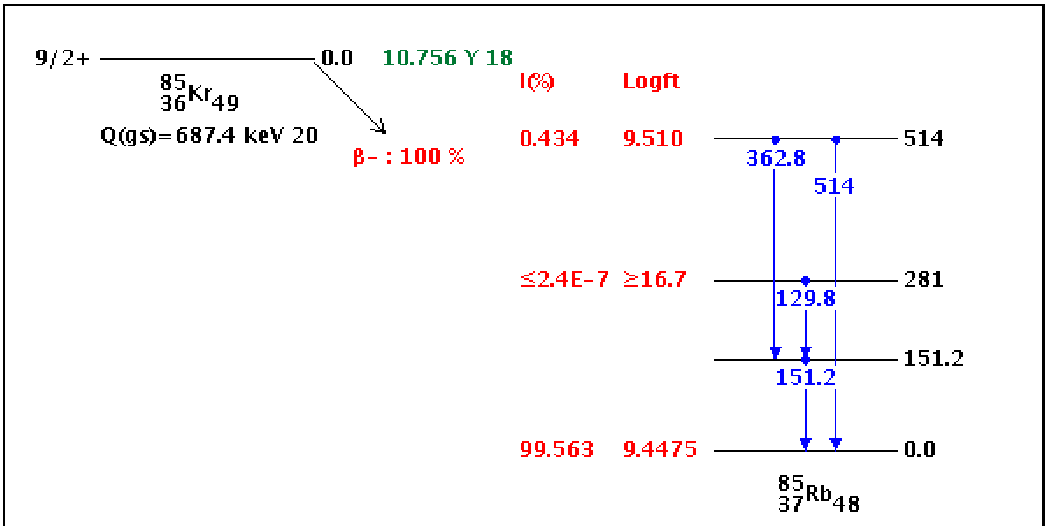

Figure 11: ^{85}Kr decay scheme.[24]

^{85}Kr decays to produce multiple gamma rays. However, none of these gammas have intensities greater than 1%.

[24] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=85KR&unc=nds.

^{154}Eu

The decay scheme for ^{154}Eu is shown in Appendix 1, Figure 40.

Table 9: ^{154}Eu decay gamma rays (with intensities greater than 1%).[25]

Gamma #	**Energy (keV)**	**Intensity (%)**	**Coincidences (Gamma #)**
1	123.0706	40.4	2, 3, 4, 5, 7, 8, 9, 10, 11
2	1274.429	34.8	1
3	723.3014	20.06	1, 5, 6, 7, 11
4	1004.76	18.01	1, 8
5	873.1834	12.08	1, 3, 8
6	996.29	10.48	3, 8
7	247.9290	6.89	1, 3, 8, 9
8	591.755	4.95	1, 4, 5, 6, 7, 9, 11
9	756.8020	4.52	1, 7, 8
10	1596.4804	1.797	1
11	692.4205	1.777	1, 3, 8

^{154}Eu has a very complex decay scheme with eleven gamma rays being produced with intensities greater than 1%. The most intense gamma (at 123 keV) shares a coincidence with all but one of the other ten gammas in Table 9. Therefore, detection of ^{154}Eu may be possible using a gamma-gamma coincidence method.

[25] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=154EU&unc=nds.

^{244}Cm

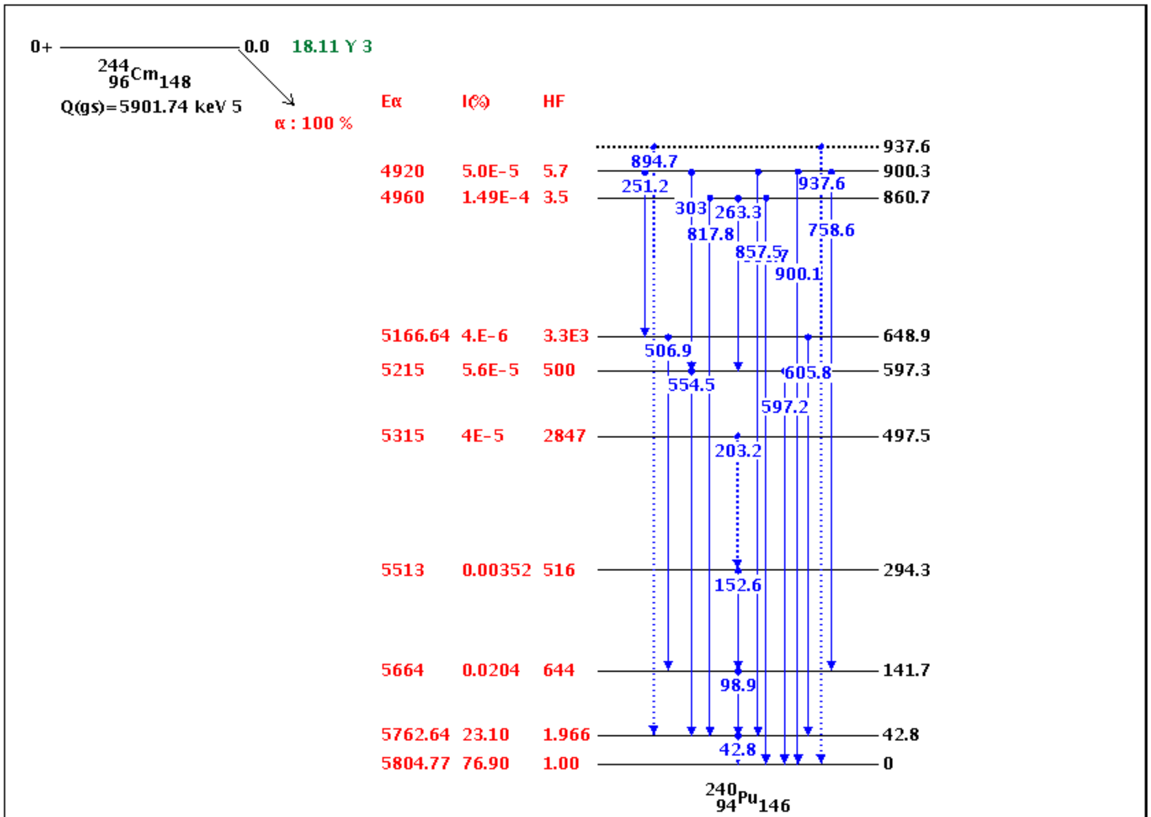

Figure 12: ^{244}Cm decay scheme.[26]

^{244}Cm is capable of producing multiple gamma rays. However, none of these gammas have intensities greater than 1%, as ^{244}Cm most often (76.9%) decays directly to the ground state of ^{240}Pu.

[26] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=244CM&unc=nds.

^{125}Sb

The decay scheme for ^{125}Sb is shown in Appendix 1, Figure 41.

Table 10: ^{125}Sb decay gamma rays (with intensities greater than 1%).[27]

Gamma #	Energy (keV)	Intensity (%)	Coincidences (Gamma #)
1	427.874	29.8	7
2	600.597	17.77	7
3	635.950	11.29	7
4	463.365	10.56	None
5	176.314	6.89	None
6	606.713	5.02	7
7	35.489	4.5	1, 2, 3, 6
8	671.441	1.803	None
9	380.452	1.527	None

^{125}Sb produces nine gamma rays with intensities greater than 1%, four of which have intensities greater than 10%. None of these top four gammas are in coincidence with each other. Therefore, ^{125}Sb may be best detected using Compton suppression methods.

[27] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=125SB&unc=nds.

^{238}Pu

The decay scheme for ^{238}Pu is shown in Appendix 1, Figure 42.

^{238}Pu is capable of producing multiple gamma rays. However, none of these gammas have intensities greater than 1%.[28]

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[28] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=238PU&unc=nds.

^{155}Eu

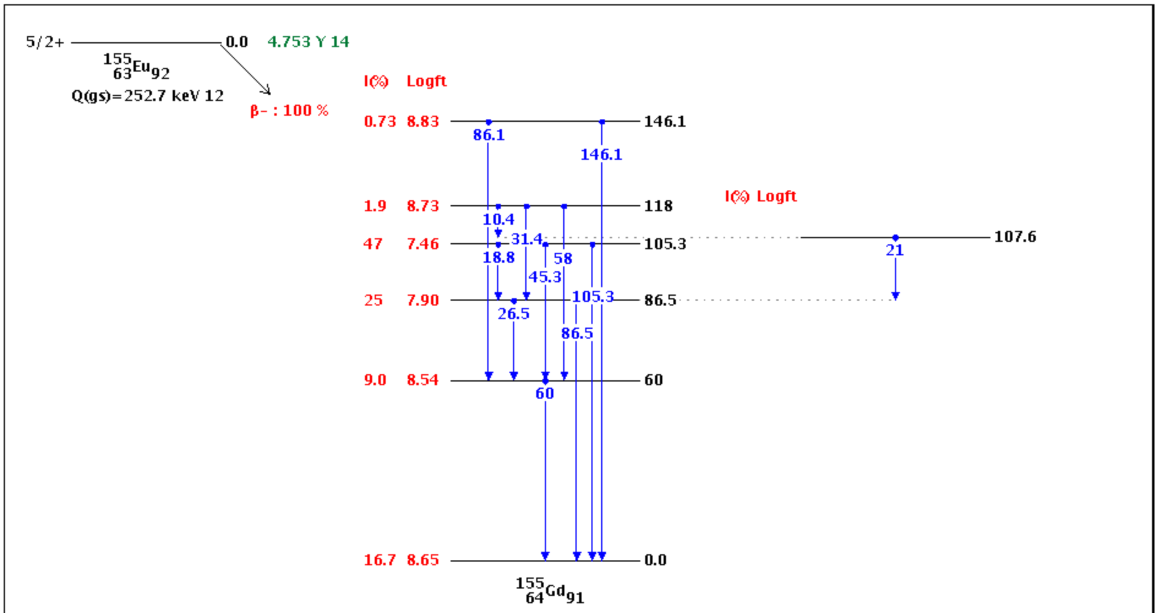

Figure 13: ^{155}Eu decay scheme.[29]

Table 11: ^{155}Eu decay gamma rays (with intensities greater than 1%).[29]

Gamma #	Energy (keV)	Intensity (%)	Coincidences (Gamma #)
1	86.5479	30.7	None
2	105.3083	21.1	None
3	45.2990	1.31	4
4	60.0086	1.22	3

^{155}Eu produces four gamma rays with intensities greater than 1%, two of which have intensities greater than 20%. These two high intensity gammas are not coincident with each other. Therefore, ^{155}Eu may be best detected using a Compton suppression system.

[29] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=155EU&unc=nds.

^{125m}Te

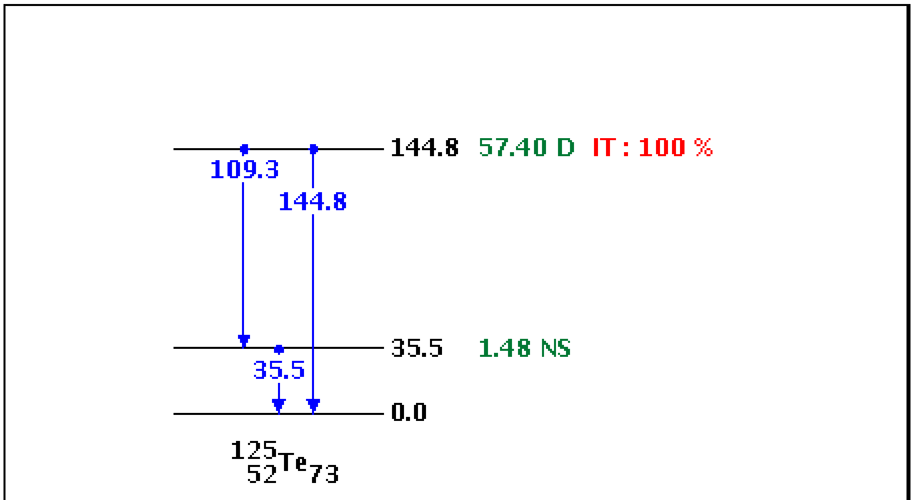

Figure 14: ^{125m}Te decay scheme.[30]

Table 12: ^{125m}Te decay gamma rays (with intensities greater than 1%).[30]

Gamma #	**Energy (keV)**	**Intensity (%)**	**Coincidences (Gamma #)**
1	35.504	6.67	None

The metastable state of ^{125}Te produces one gamma with an intensity greater than 1%. In addition to this 36 keV gamma, a second gamma is produced in coincidence (109 keV). However, this coincident gamma has an intensity less than 1%. Because the rate of this coincidence is much lower than the rate of production of the 36 keV gamma, Compton suppression will be the most effective method of detecting ^{125m}Te.

[30] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=125TE&unc=nds.

^{144m}Pr

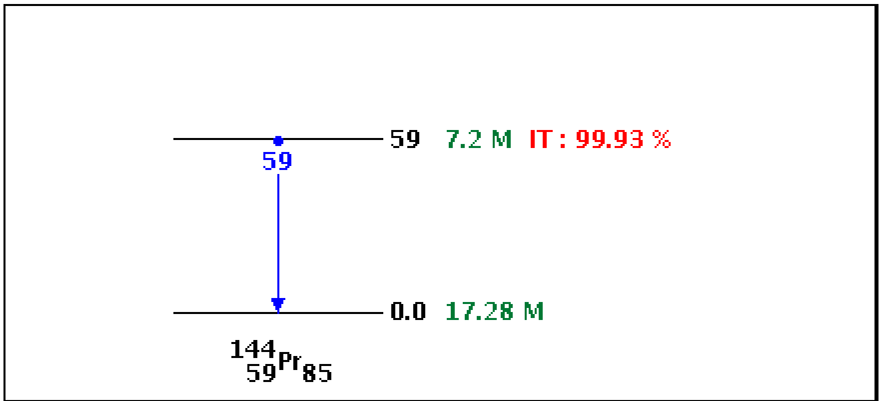

Figure 15: ^{144m}Pr decay scheme.[31]

The metastable state of ^{144}Pr produces one possible gamma ray. However, this gamma has an intensity less than 1%.

[31] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=144PR&unc=nds.

^{241}Am

The decay scheme for ^{241}Am is shown in Appendix 1, Figure 43.

Table 13: ^{241}Am decay gamma rays (with intensities greater than 1%).[32]

Gamma #	**Energy (keV)**	**Intensity (%)**	**Coincidences (Gamma #)**
1	59.5409	35.9	None
2	26.3446	2.27	None

^{241}Am is capable of producing numerous gamma rays. However, only two of these gammas have intensities greater than 1%. Additionally, these gammas are not in coincidence with each other. Therefore, ^{241}Am may be best detected using a Compton suppression system.

[32] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=241AM&unc=nds.

^{3}H

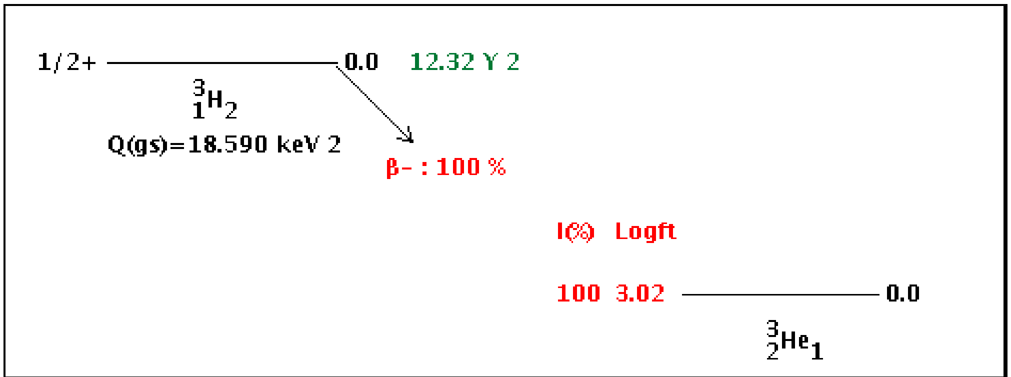

Figure 16: ^{3}H decay scheme.[33]

Tritium (^{3}H) is a beta emitter, producing no gamma radiation.

[33] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=3H&unc=nds.

^{240}Pu

The decay scheme for ^{240}Pu is shown in Appendix 1, Figure 44.

^{240}Pu decays to produce multiple gamma rays. However, none of these gammas have intensities greater than 1%.[34]

[34] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=240PU&unc=nds.

^{242}Cm

The decay scheme for ^{242}Cm is shown in Appendix 1, Figure 45.

^{242}Cm is capable of producing numerous gamma rays. However, none of these gammas have intensities greater than 1%.[35]

[35] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=242CM&unc=nds.

^{151}Sm

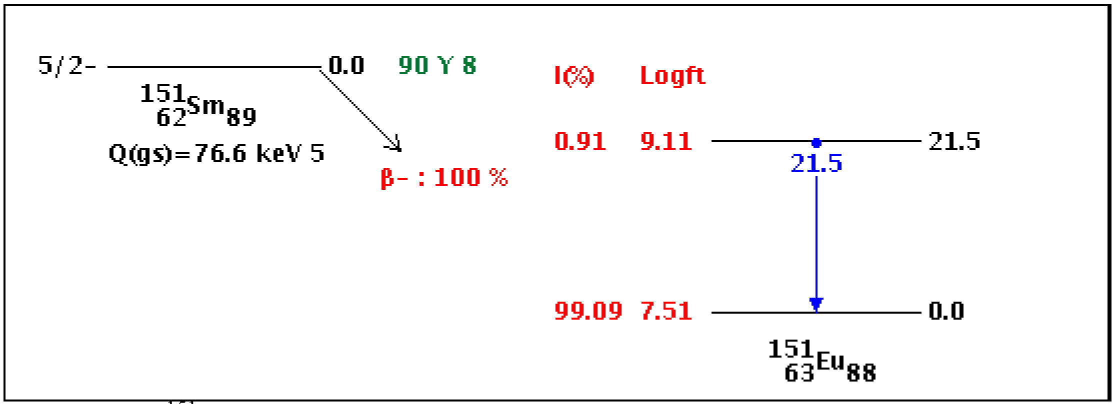

Figure 17: ^{151}Sm decay scheme.[36]

^{151}Sm decays by beta emission and is capable of producing one gamma ray. However, this gamma has an intensity less than 1%, as ^{151}Sm most often (99.09%) decays directly to the ground state of ^{151}Eu.

[36] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=151SM&unc=nds.

^{239}Pu

The decay scheme for ^{239}Pu is shown in Appendix 1, Figure 46.

^{239}Pu produces nearly 200 possible gamma rays.[37] Of these, none have an intensity greater than 1%. Additionally, most of the possible gammas are in complex coincidences with many other gammas, increasing the difficulty of detecting ^{239}Pu by gamma spectroscopy.

[37] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=239PU&unc=nds.

^{110m}Ag

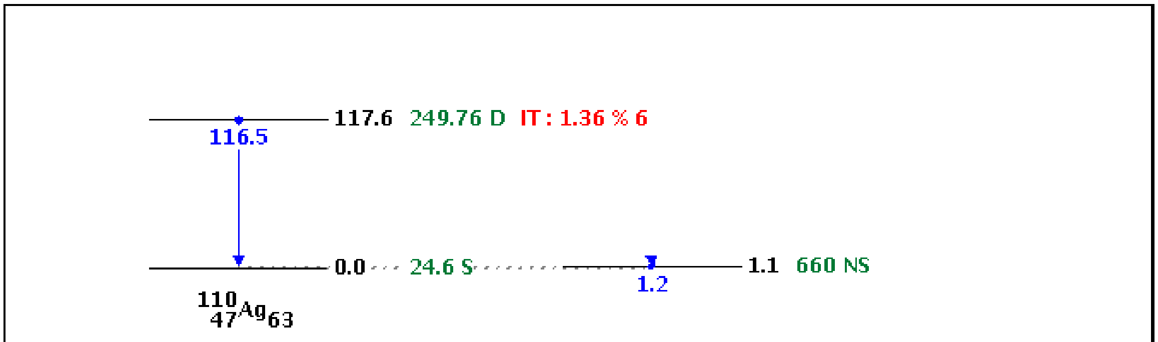

Figure 18: ^{110m}Ag decay schemes. ^{110m}Ag decays by both beta emission (98.56%, shown in Appendix 1, Figure 47) and isomeric transition (1.36%, shown here).[38]

Table 14: ^{110m}Ag decay gamma rays (with intensities greater than 1%).[38]

Gamma #	Energy (keV)	Intensity (%)	Coincidences (Gamma #)
1	657.76	94.3	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13, 14, 16
2	884.6781	72.7	1, 3, 4, 5, 6, 8, 13, 14
3	937.485	34.2	1, 2, 13
4	1384.2931	24.9	1, 2
5	763.9424	22.62	1, 2, 7, 9, 10, 12, 14
6	706.6760	16.33	1, 2, 8, 9, 11, 12, 16
7	1505.0280	13.60	1, 5
8	677.6217	10.56	1, 2, 6
9	818.0244	7.34	1, 5, 6, 10, 11, 13
10	687.0091	6.44	1, 5, 9, 12
11	744.2755	4.77	1, 6, 9, 12
12	1475.7792	4.17	5, 6, 10, 11, 13
13	446.812	3.62	1, 2, 3, 9, 12
14	620.3553	2.67	1, 2, 5
15	1.16	1.36	None
16	1562.2940	1.244	1, 6

[38] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=110AG&unc=nds.

The metastable state of ^{110}Ag may decay by both beta emission and isomeric transition. While decay by beta emission is more likely (98.56%) than isomeric transition (1.36%), both decay modes produce gammas with intensities greater than 1%. All of these possible gammas are shown in Table 14.

Of the sixteen gammas with intensities greater than 1%, all but two share coincidences with the most intense gamma (658 keV). Therefore, ^{110m}Ag is an excellent candidate for detection by gamma-gamma coincidence methods.

^{239}Np

The decay scheme for ^{239}Np is shown in Appendix 1, Figure 48.

Table 15: ^{239}Np decay gamma rays (with intensities greater than 1%).[39]

Gamma #	**Energy (keV)**	**Intensity (%)**	**Coincidences (Gamma #)**
1	106.123	26.3	2, 3, 4
2	277.599	14.44	1, 5, 8
3	228.183	11.14	1, 5, 8
4	209.753	3.42	1, 5, 8
5	4.2	2.7	2, 3, 4
6	334.310	2.060	None
7	315.880	1.600	None
8	61.460	1.3	2, 3, 4

^{239}Np is capable of producing numerous gamma rays. Eight of these gammas have intensities greater than 1%. Of these gammas, the top five share coincidences and have similar intensities. Therefore, ^{239}Np may be best detected by gamma-gamma coincidence methods.

[39] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=239NP&unc=nds.

^{243}Am

The decay scheme for ^{243}Am is shown in Appendix 1, Figure 49.

Table 16: ^{243}Am decay gamma rays (with intensities greater than 1%).[40]

Gamma #	**Energy (keV)**	**Intensity (%)**	**Coincidences (Gamma #)**
1	74.66	67.2	None
2	43.53	5.90	None

^{243}Am decays to produce two gammas with intensities greater than 1%. These two gammas are not in coincidence with each other. Therefore, ^{243}Am may be best measured using a Compton suppression system.

[40] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=243AM&unc=nds.

^{243}Cm

The decay scheme for ^{243}Cm is shown in Appendix 1, Figure 50.

Table 17: ^{243}Cm decay gamma rays (with intensities greater than 1%).[41]

Gamma #	Energy (keV)	Intensity (%)	Coincidences (Gamma #)
1	277.599	14.0	None
2	228.183	10.6	None
3	209.753	3.29	None

^{243}Cm decays to produce multiple gamma rays. However, only three of these gammas have intensities greater than 1%. Additionally, none of these three gammas are in coincidence with each other. Therefore, ^{243}Cm may be best detected using a Compton suppression system.

[41] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=243CM&unc=nds.

^{95}Nb

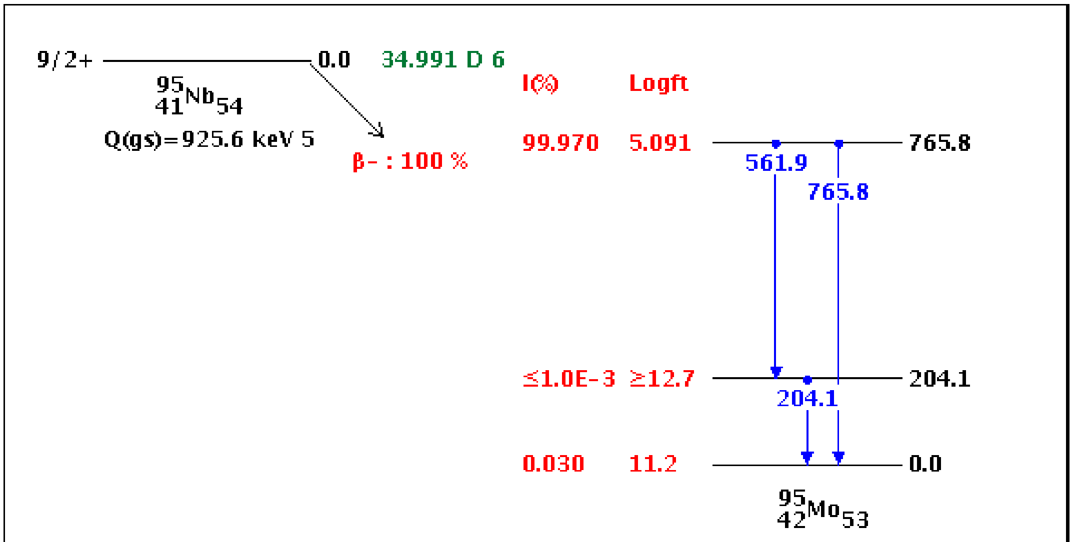

Figure 19: ^{95}Nb decay scheme.[42]

Table 18: ^{95}Nb decay gamma rays (with intensities greater than 1%).[42]

Gamma #	Energy (keV)	Intensity (%)	Coincidences (Gamma #)
1	765.803	99.808	None

^{95}Nb produces three gamma rays, with only one gamma having an intensity greater than 1%. This gamma is not in coincidence with the other two gammas. Therefore, ^{95}Nb may be best detected using a Compton suppression system.

[42] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=95NB&unc=nds.

^{99}Tc

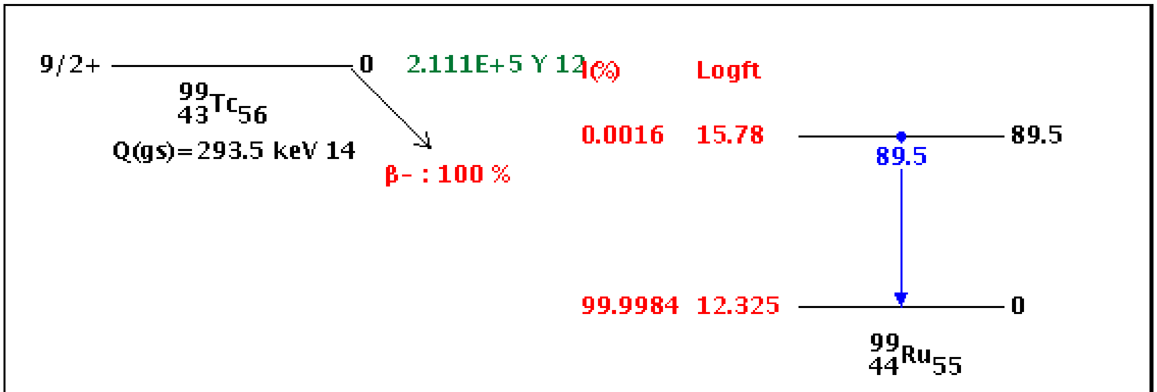

Figure 20: ^{99}Tc decay scheme.[43]

^{99}Tc decays by beta emission and is capable of producing one gamma ray. However, this gamma has an intensity less than 1%, as ^{99}Tc most often (99.99%) decays directly to the ground state of ^{99}Ru.

43 National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=99TC&unc=nds.

^{121m}Sn

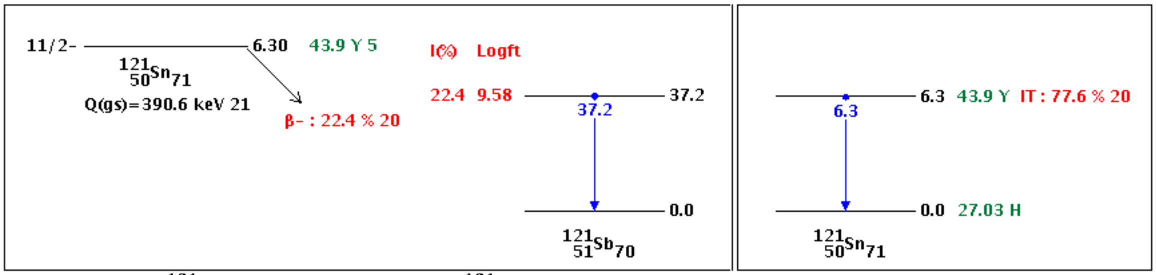

Figure 21: ^{121m}Sn decay schemes. ^{121m}Sn decays by both beta emission (22.4%, left) and isomeric transition (77.6%, right).[44]

Table 19: ^{121m}Sn decay gamma rays (with intensities greater than 1%).[44]

Gamma #	Energy (keV)	Intensity (%)	Coincidences (Gamma #)
1	37.15	1.85	None

The metastable state of ^{121}Sn may decay by both beta emission or isomeric transition. While decay by isomeric transition is more likely (77.6%) than beta emission (22.4%), only the beta emission produces a gamma ray with an intensity greater than 1%. As this gamma ray does not share any coincidences, ^{121m}Sn may be best detected by a Compton suppression system.

[44] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=121SN&unc=nds.

^{127m}Te

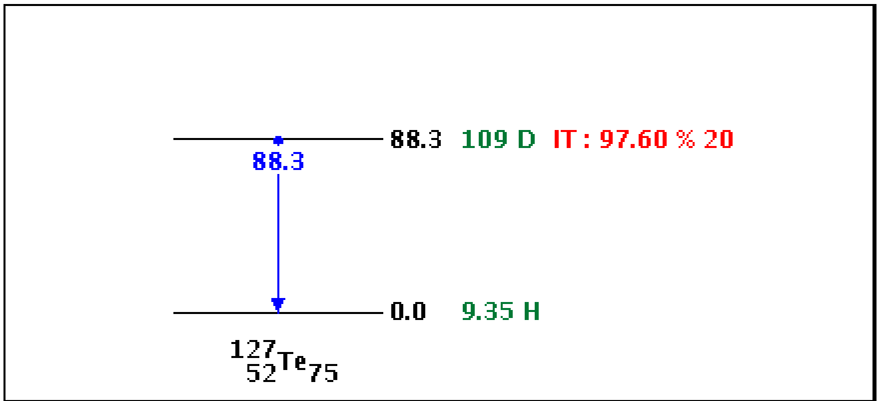

Figure 22: ^{127m}Te decay scheme.[45]

The metastable state of ^{127}Te produces one gamma ray. However, this gamma has an intensity of less than 1%.

[45] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=127TE&unc=nds.

^{127}Te

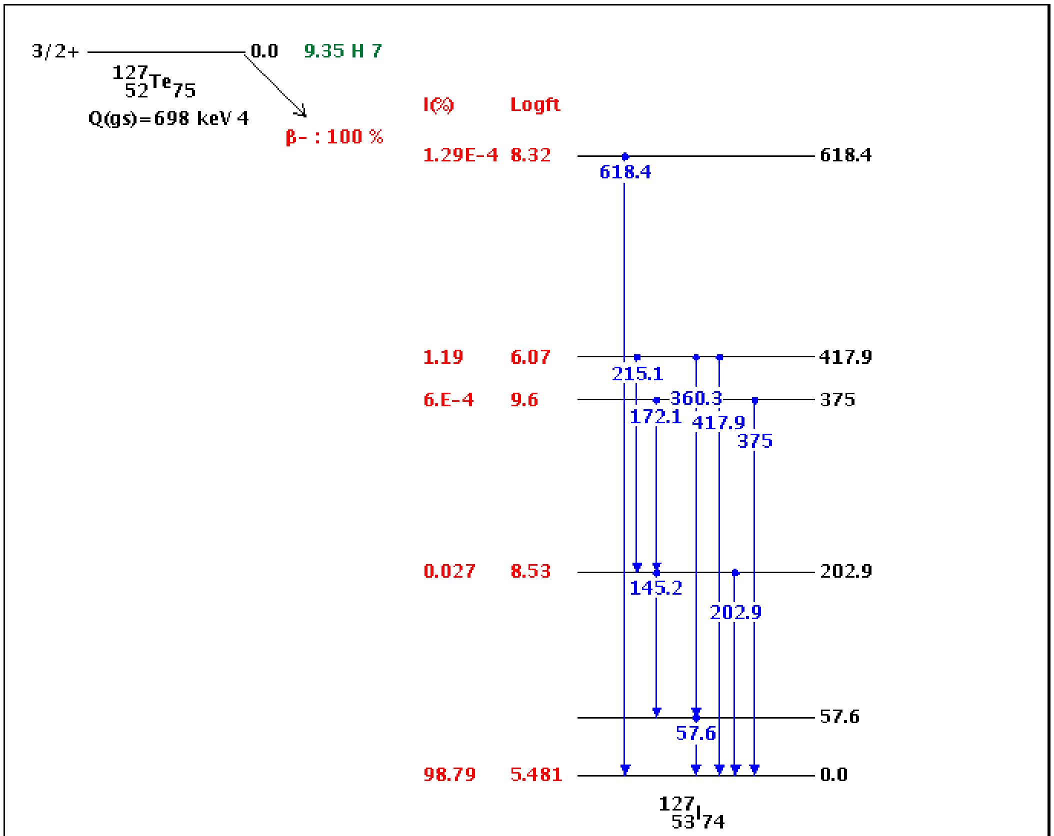

Figure 23: ^{127}Te decay scheme.[46]

^{127}Te decays to produce multiple gammas. However, none of these gammas have intensities greater than 1%.

46 National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=127TE&unc=nds.

^{121}Sn

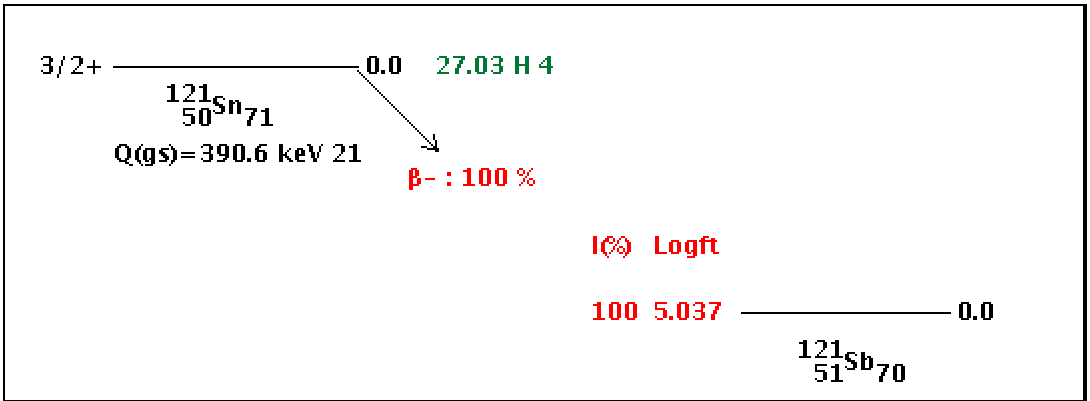

Figure 24: ^{121}Sn decay scheme.[47]

^{121}Sn decays by beta emission, producing no gamma radiation.

[47] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=121SN&unc=nds.

^{242m}Am

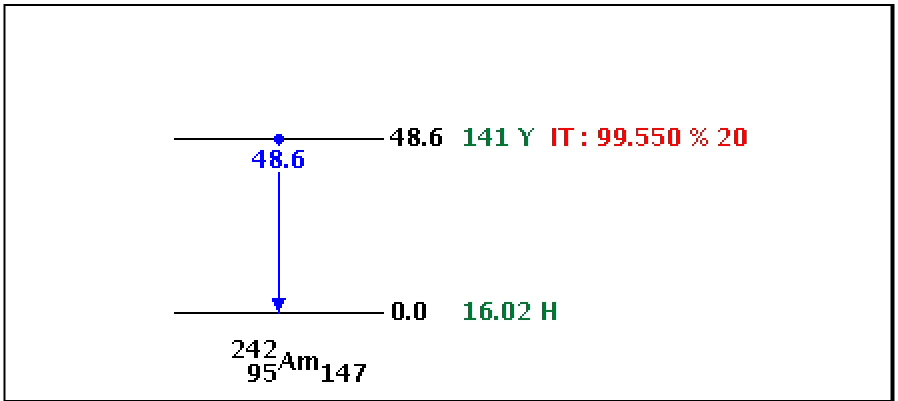

Figure 25: ^{242m}Am decay scheme.[48]

The metastable state of ^{242}Am decays by isomeric transition, producing one gamma ray. However, this gamma does not have an intensity greater than 1%.

[48] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=242AM&unc=nds.

^{242}Am

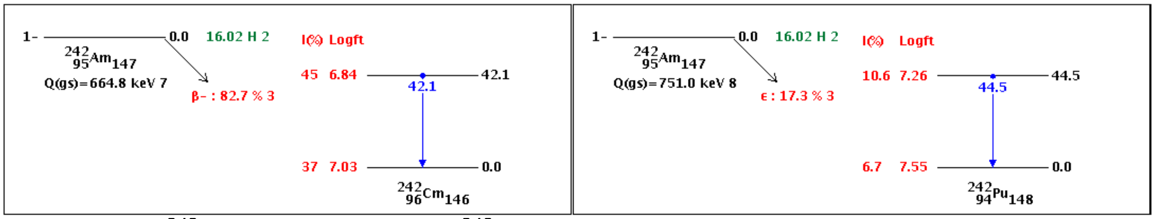

Figure 26: ^{242}Am decay schemes. ^{242}Am decays by both beta emission (82.7%, left) and electron capture (17.3%, right).[49]

^{242}Am may decay by either beta emission or electron capture. Decay by beta emission is more likely (82.7%) than electron capture (17.3%). Both of these decay modes produce one gamma ray. However, neither of these gammas have an intensity greater than 1%.

[49] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=242AM&unc=nds.

^{95}Zr

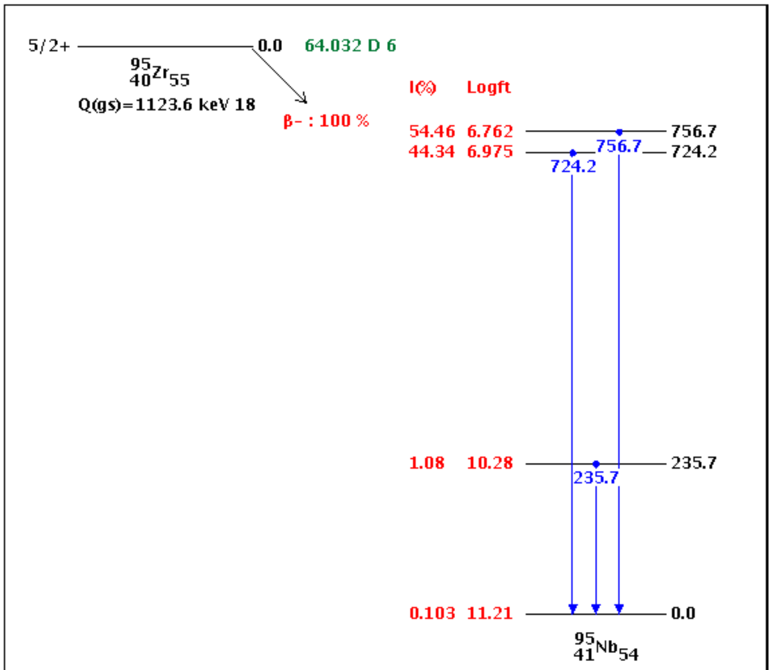

Figure 27: ^{95}Zr decay scheme.[50]

Table 20: ^{95}Zr decay gamma rays (with intensities greater than 1%).[50]

Gamma #	Energy (keV)	Intensity (%)	Coincidences (Gamma #)
1	756.725	54.38	None
2	724.192	44.27	None

^{95}Zr produces two gamma rays with intensities greater than 1%. These gammas do not occur in coincidence with each other. Therefore, ^{95}Zr may be best detected using a Compton suppression system.

[50] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=95ZR&unc=nds.

^{152}Eu

The ^{152}Eu decay schemes for both electron capture and beta emission are shown in Appendix 1, Figure 51 and Figure 52.

Table 21: ^{152}Eu decay gamma rays (with intensities greater than 1%).[51]

Gamma #	Energy (keV)	Intensity (%)	Coincidences (Gamma #)
1	121.7817	28.67	3, 4, 5, 8, 9, 10, 14
2	344.2785	26.6	6, 11, 12, 13
3	1408.006	21.07	1
4	964.079	14.65	1, 10
5	1112.069	13.69	1
6	778.9040	12.96	2
7	1085.869	10.24	10
8	244.6975	7.61	1, 9, 10, 14
9	867.373	4.26	1, 8
10	443.965	2.830	1, 4, 7, 8
11	411.1163	2.237	2
12	1089.737	1.730	2
13	1299.140	1.625	2
14	1212.948	1.426	1, 8

^{152}Eu may decay by either electron capture or beta emission. Electron capture occurs more frequently (72.1%) than beta emission (27.9%), but both decay modes produces gamma rays with intensities greater than 1%.

Of the gamma rays listed in Table 21, four of the first five gammas are in coincidence. Additionally, the second gamma (344 keV) is in coincidence with the sixth (779 keV). These coincidences all occur with high intensities, as each of the gammas in these coincidences have intensities greater than 10%. Therefore, ^{152}Eu may be detected by gamma-gamma coincidence methods.

[51] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=152EU&unc=nds.

^{119m}Sn

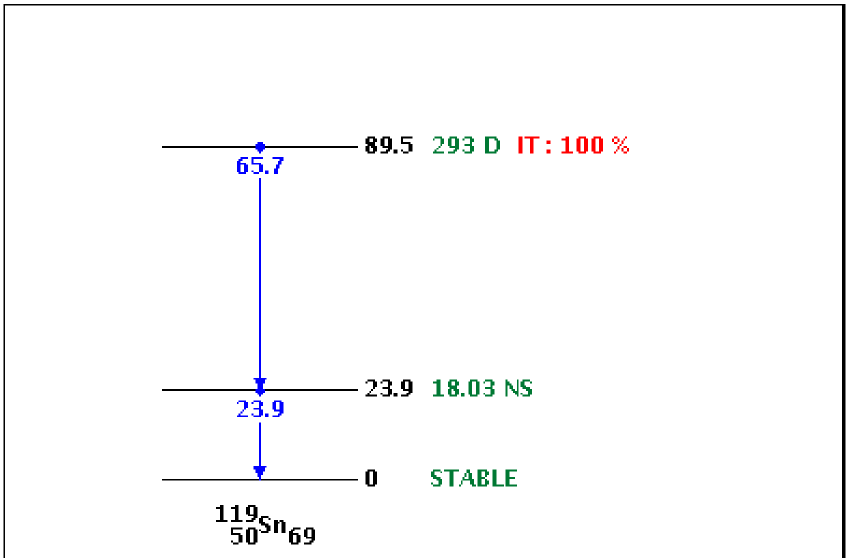

Figure 28: ^{119m}Sn decay scheme.[52]

Table 22: ^{119m}Sn decay gamma rays (with intensities greater than 1%).[52]

Gamma #	Energy (keV)	Intensity (%)	Coincidences (Gamma #)
1	23.875	16.5	None

The metastable state of ^{119}Sn is capable of producing two gamma rays. However, only one of these gammas has an intensity greater than 1%. Therefore, ^{119m}Sn may be best detected using a Compton suppression system.

[52] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=119SN&unc=nds.

^{123}Sn

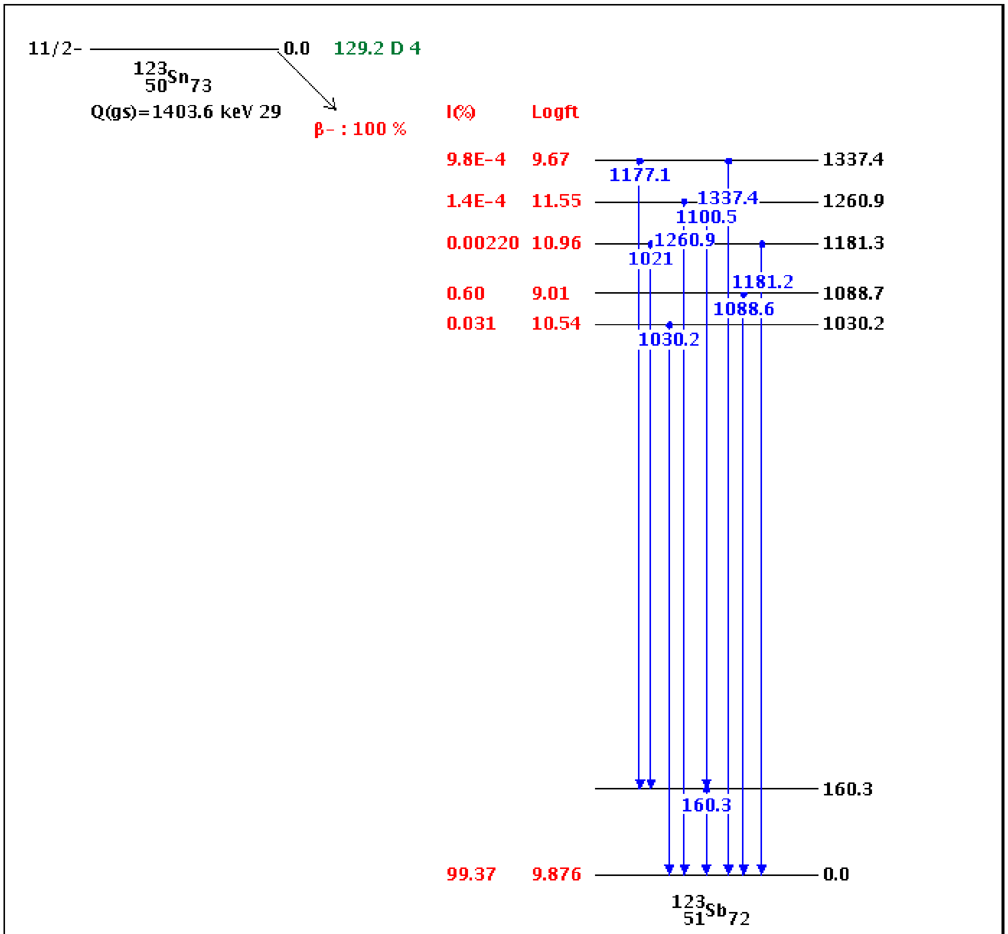

Figure 29: ^{123}Sn decay scheme.[53]

^{123}Sn decays to produce multiple gammas. However, none of these gammas have intensities greater than 1%.

[53] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=123SN&unc=nds.

^{237}U

The decay scheme for ^{237}U is shown in Appendix 1, Figure 53.

Table 23: ^{237}U decay gamma rays (with intensities greater than 1%).[54]

Gamma #	**Energy (keV)**	**Intensity (%)**	**Coincidences (Gamma #)**
1	59.5409	34.5	2, 4, 5
2	208.005	21.2	1, 3, 5
3	26.3446	2.43	2, 4, 5
4	164.61	1.86	1, 3, 5
5	64.83	1.282	1, 2, 3, 4
6	332.35	1.2	None

^{237}U decays to produce numerous gamma rays. Of these, six have intensities greater than 1%. The two gammas with the highest intensities (60 keV and 208 keV) are also in coincidence. Therefore, ^{237}U may be measured using gamma-gamma coincidence methods.

54 National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=237U&unc=nds.

^{242}Pu

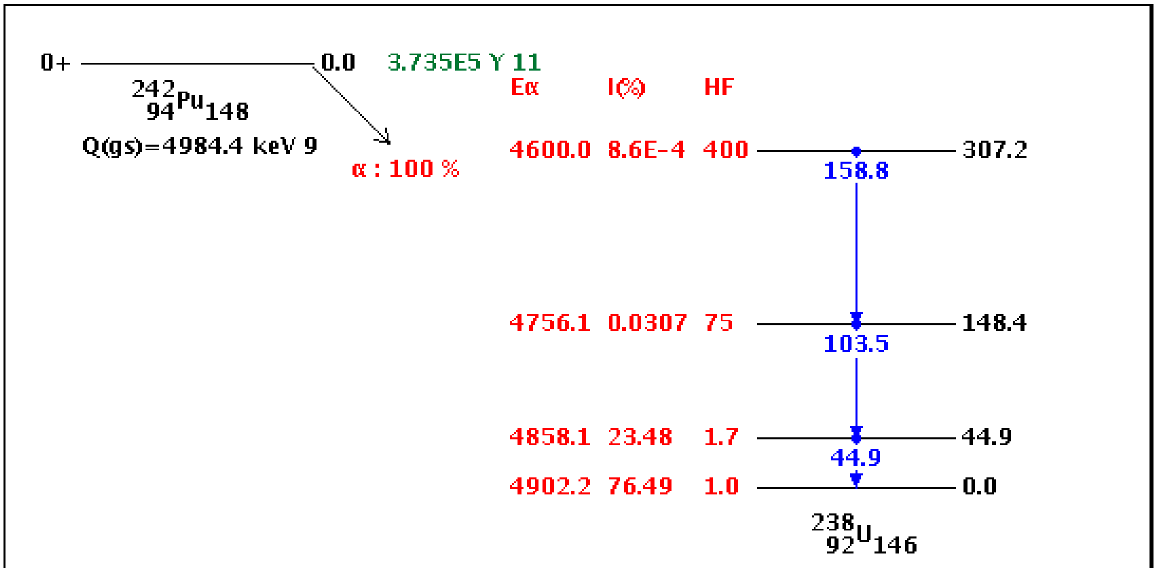

Figure 30: ^{242}Pu decay scheme.[55]

^{242}Pu decays to produce three possible gamma rays. However, none of these gammas have intensities greater than 1%.

[55] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=242PU&unc=nds.

^{110}Ag

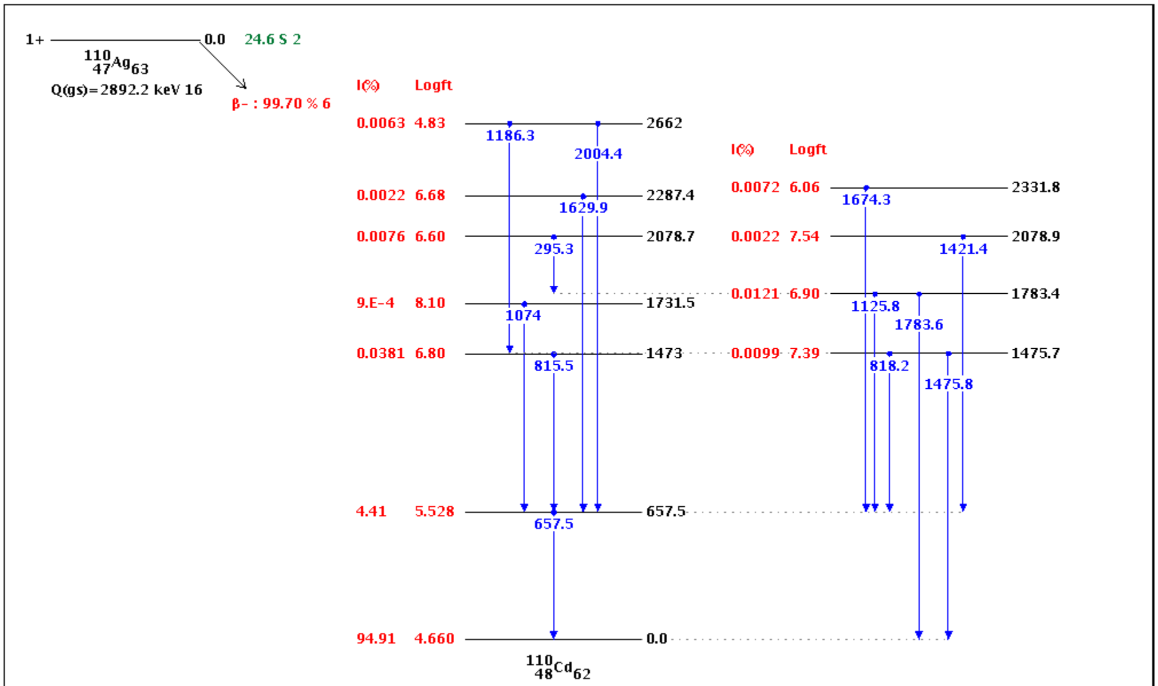

Figure 31: ^{110}Ag decay scheme.[56]

Table 24: ^{110}Ag decay gamma rays (with intensities greater than 1%).[56]

Gamma #	Energy (keV)	Intensity (%)	Coincidences (Gamma #)
1	657.5	4.50	None

^{110}Ag decays to produce multiple possible gamma rays. However, only one of these gammas has an intensity greater than 1%. Because this gamma does not share any strong coincidences, ^{110}Ag may be measured by a Compton suppression system.

[56] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=110AG&unc=nds.

^{93}Zr

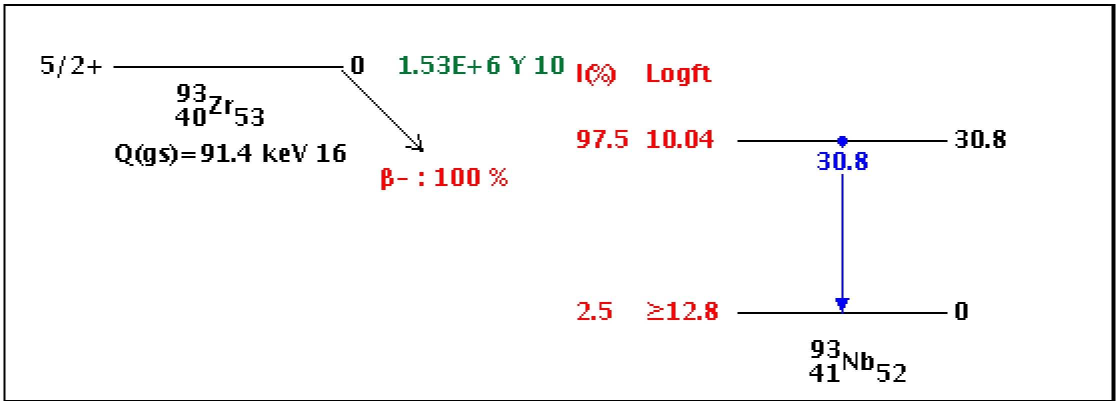

Figure 32: ^{93}Zr decay scheme.[57]

^{93}Zr decays by beta emission and is capable of producing one gamma ray. However, this gamma has an intensity less than 1%.

[57] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=93ZR&unc=nds.

^{91}Y

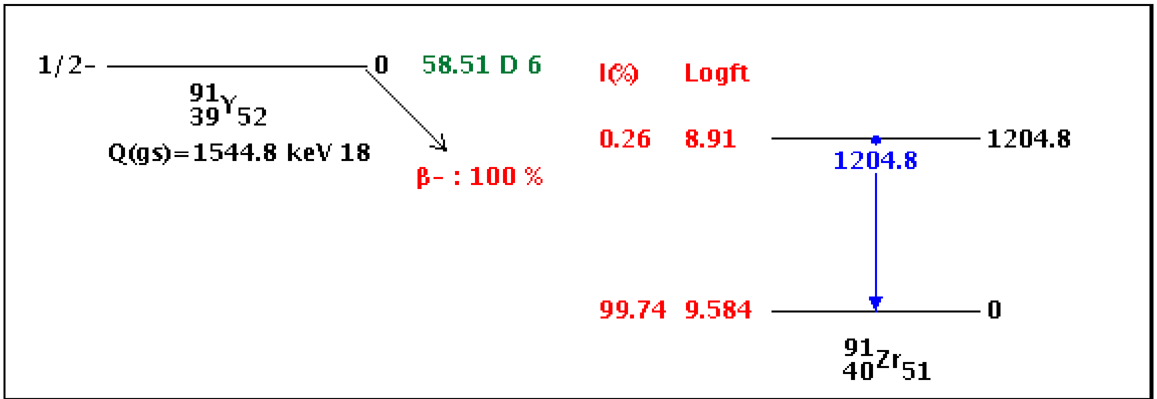

Figure 33: ^{91}Y decay scheme.[58]

^{91}Y decays by beta emission and is capable of producing one gamma ray. However, this gamma has an intensity less than 1%, as ^{91}Y most often (99.74%) decays directly to the ground state of ^{91}Zr.

[58] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=91Y&unc=nds.

[234]U

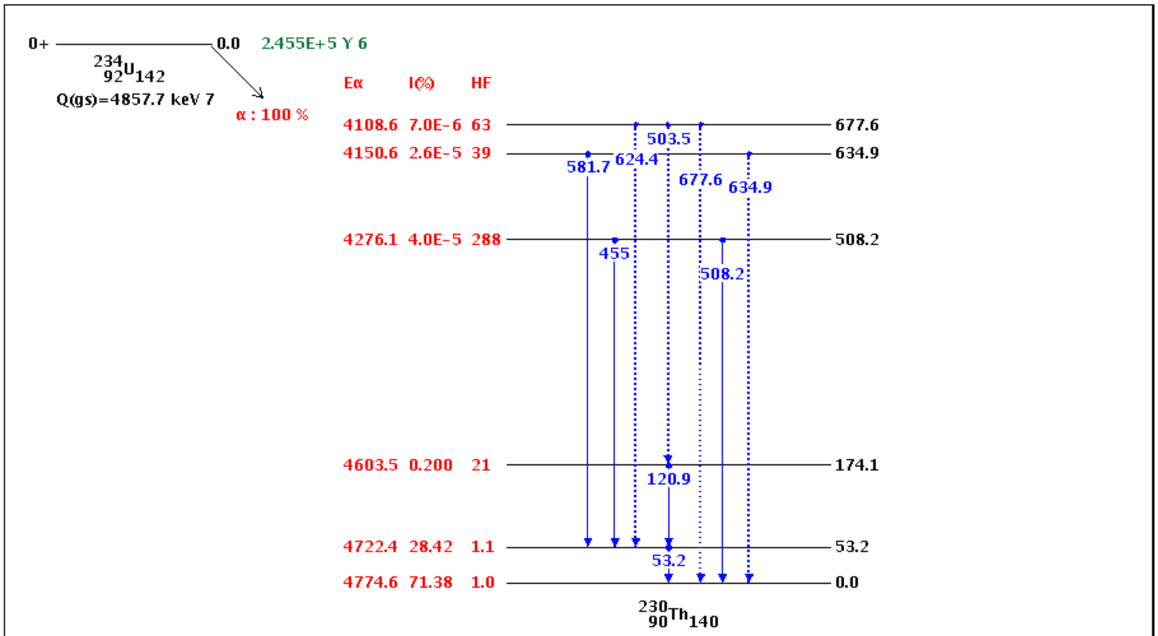

Figure 34: ^{234}U decay scheme.[59]

^{234}U decays by alpha emission and is capable of producing multiple gamma rays. However, none of these gammas have intensities greater than 1%.

[59] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=234U&unc=nds.

^{126m}Sb

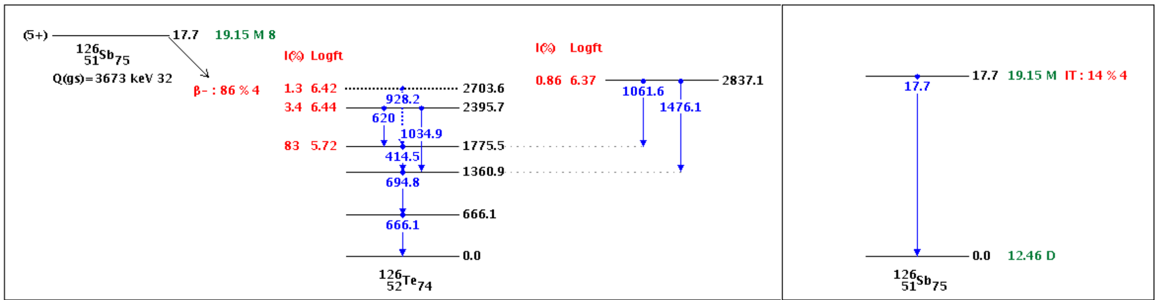

Figure 35: ^{126m}Sb decay schemes. ^{126m}Sb decays by both beta decay (86%, left) and isomeric transmission (14%, right).[60]

Table 25: ^{126m}Sb decay gamma rays (with intensities greater than 1%).[60]

Gamma #	Energy (keV)	Intensity (%)	Coincidences (Gamma #)
1	666.1	86	2, 3, 4, 5, 6
2	414.5	86	1, 3, 5, 6
3	694.8	82	1, 2, 4, 5, 6
4	1034.9	1.80	1, 3
5	620.0	1.54	1, 2, 3
6	928.2	1.3	1, 2, 3

The metastable state of ^{126}Sb may decay by either beta decay or isomeric transition. The beta decay mode occurs more often (86%) than the isomeric transition mode (14%). Additionally, only the beta decay mode produces gammas with intensities greater than 1%.

The six gammas that do have intensities greater than 1% are in very strong coincidences with each other. The first three gammas all are in coincidence with each other and have intensities exceeding 80%. Therefore, ^{126m}Sb is an excellent candidate for detection by gamma-gamma coincidence methods.

[60] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=126SB&unc=nds.

^{126}Sn

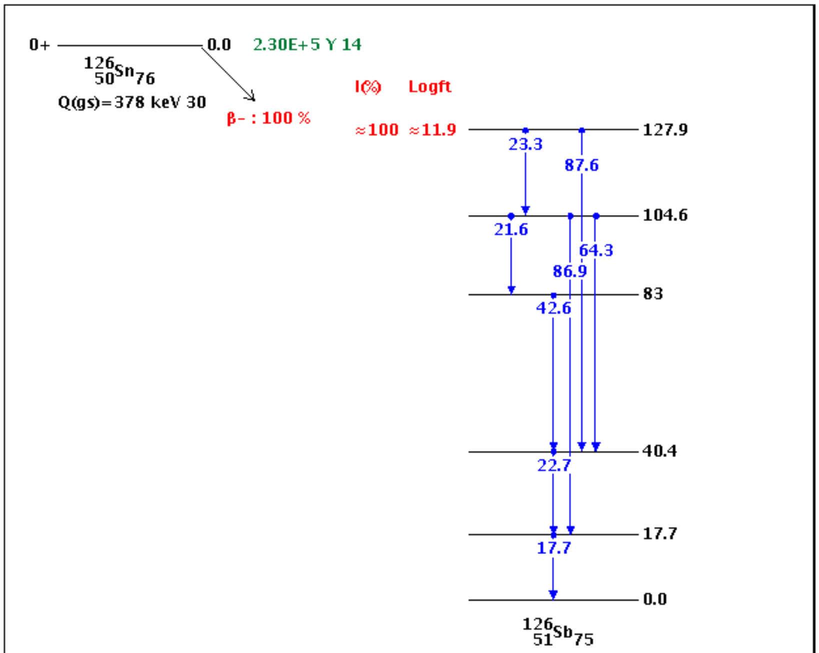

Figure 36: ^{126}Sn decay scheme.[61]

Table 26: ^{126}Sn decay gamma rays (with intensities greater than 1%).[61]

Gamma #	**Energy (keV)**	**Intensity (%)**	**Coincidences (Gamma #)**
1	87.567	37	None
2	64.281	9.6	4
3	86.938	8.9	4
4	23.280	6.4	2, 3, 5
5	21.646	1.26	4

^{126}Sn decays to produce five gamma rays with intensities greater than 1%. The gamma with the highest intensity at 88 keV does not share any coincidences with other gammas having intensities greater than 1%. Therefore, ^{126}Sn may be detected using a Compton suppression system.

[61] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=126SN&unc=nds.

^{135}Cs

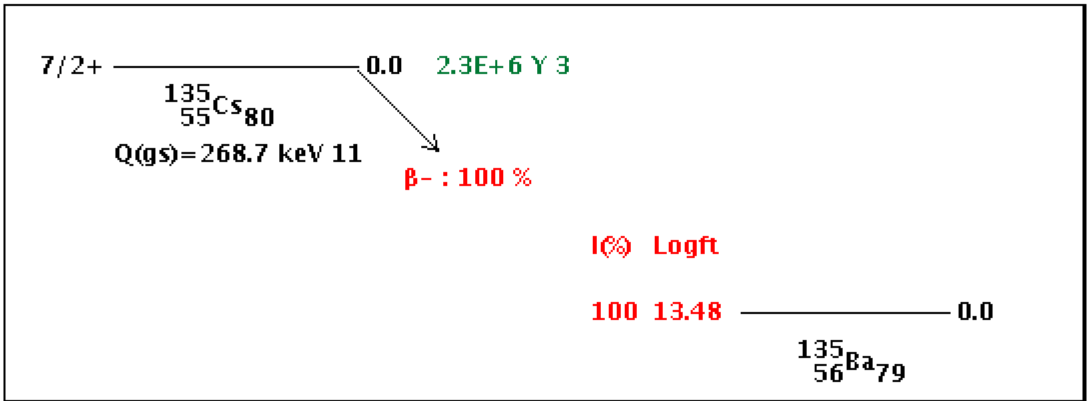

Figure 37: ^{135}Cs decay scheme.[62]

^{135}Cs decays by beta emission, producing no gamma radiation.

[62] National Nuclear Data Center, Brookhaven National Laboratory, Chart of Nuclides, http://www.nndc.bnl.gov/chart/decaysearchdirect.jsp?nuc=135CS&unc=nds.

Conclusion

The fifty nuclides with the highest relative activities in spent PWR and BWR fuels were characterized with regard to the most effective of either Compton suppression or gamma-gamma coincidence detection schemes. Of these fifty nuclides, 16 are well-suited for detection by anti-coincidence (Compton suppression) methods, and 8 are well-suited for detection by coincidence (gamma-gamma) methods. The remaining nuclides considered (26 of the 50 nuclides) do not produce gamma radiation or produce gamma radiation with absolute intensities less than 1%.

FUTURE WORK

To further enhance the detection and identification of gamma radiation emitted by spent nuclear fuel, further studies could be conducted to determine the most appropriate energy gating schemes for each nuclide. Energy gating could improve detection capabilities by eliminating undesired coincidences in both Compton suppression and gamma-gamma coincidence methods.

Additionally, future work could focus on the actual activities of each nuclide to determine the most viable nuclide candidates for detection in real spent fuel. In this analysis only the relative activities were considered, without regard for the actual activities found in a given sample.

Appendix 1

ADDITIONAL NUCLIDE LEVEL DIAGRAMS[63]

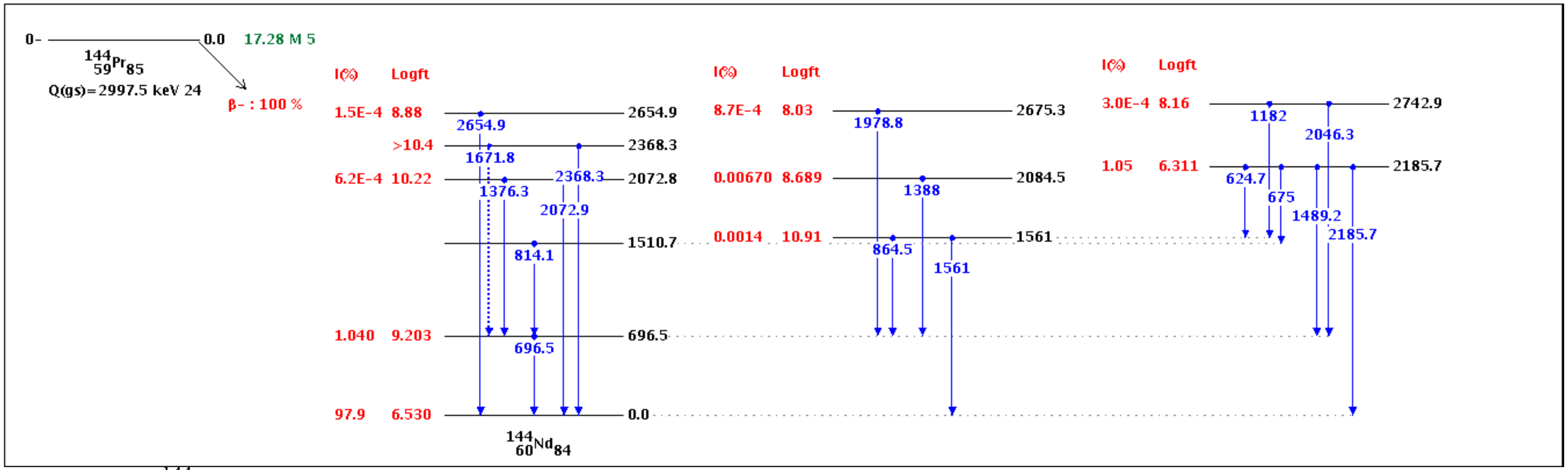

Figure 38: [144]Pr decay scheme.

[63] All level diagrams: National Nuclear Data Center, Brookhaven National Laboratory, information extracted from the Chart of Nuclides database, http://www.nndc.bnl.gov/chart/.

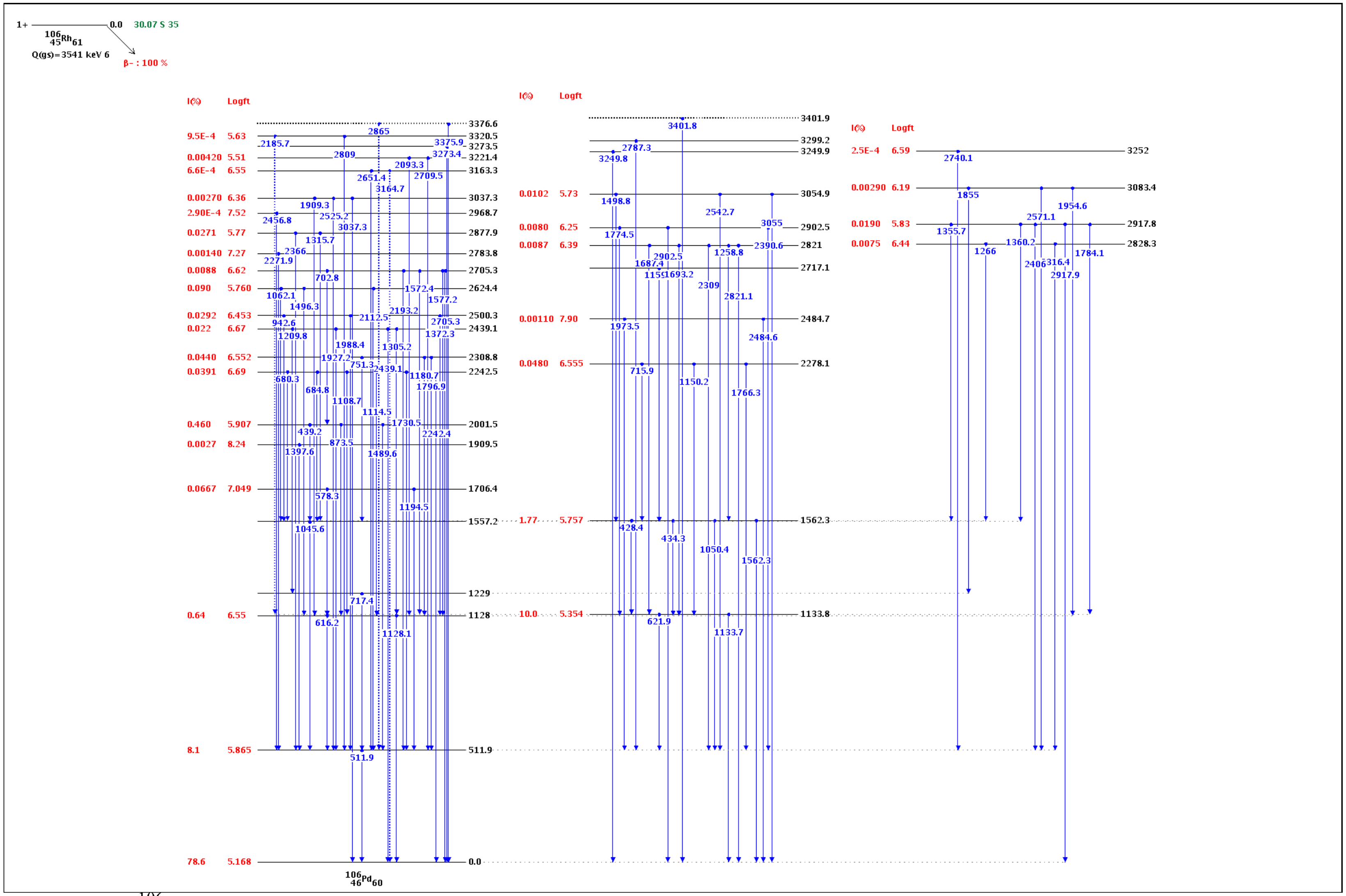

Figure 39: ^{106}Rh decay scheme.

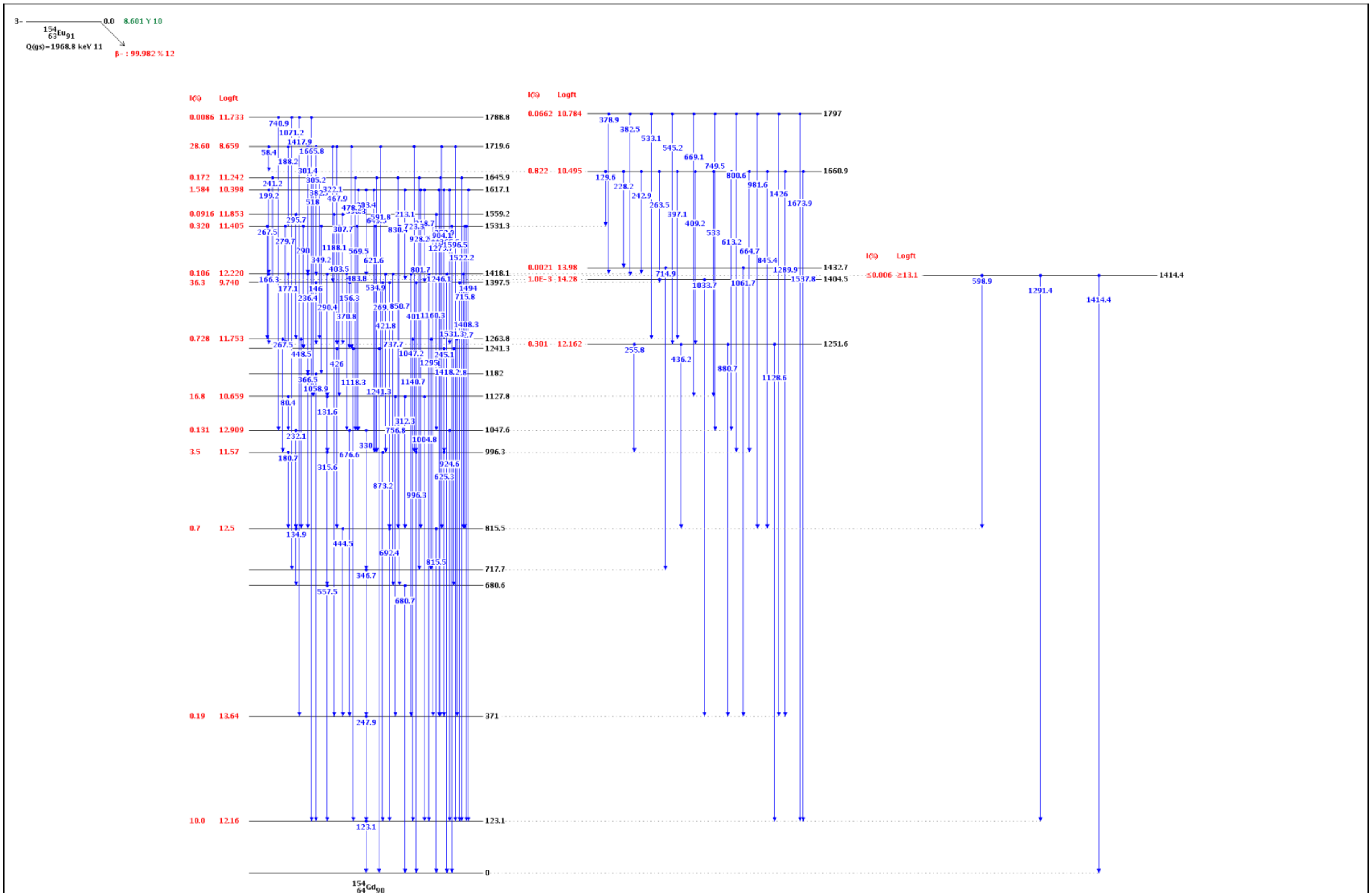

Figure 40: ^{154}Eu decay scheme.

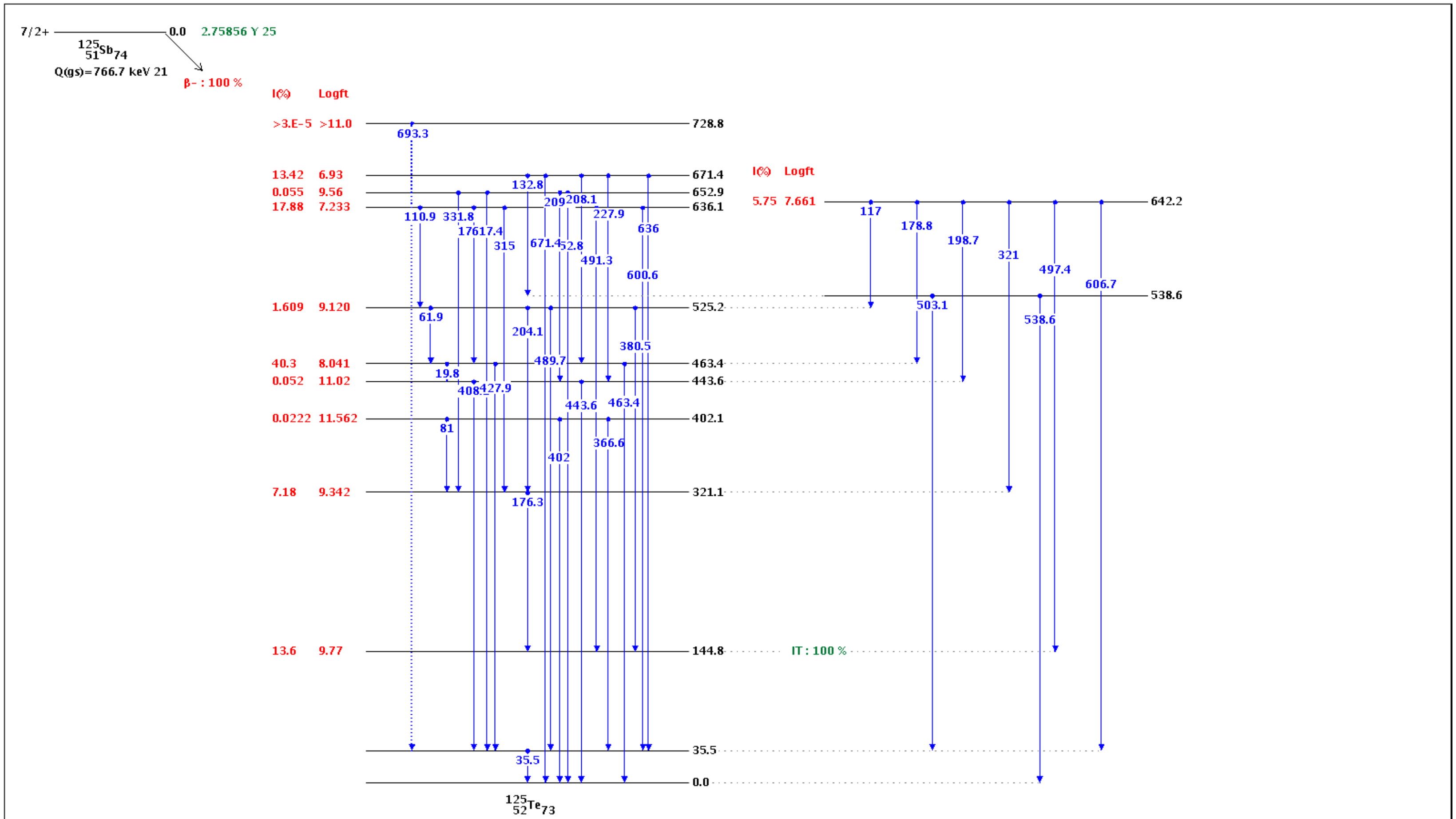

Figure 41: ^{125}Sb decay scheme.

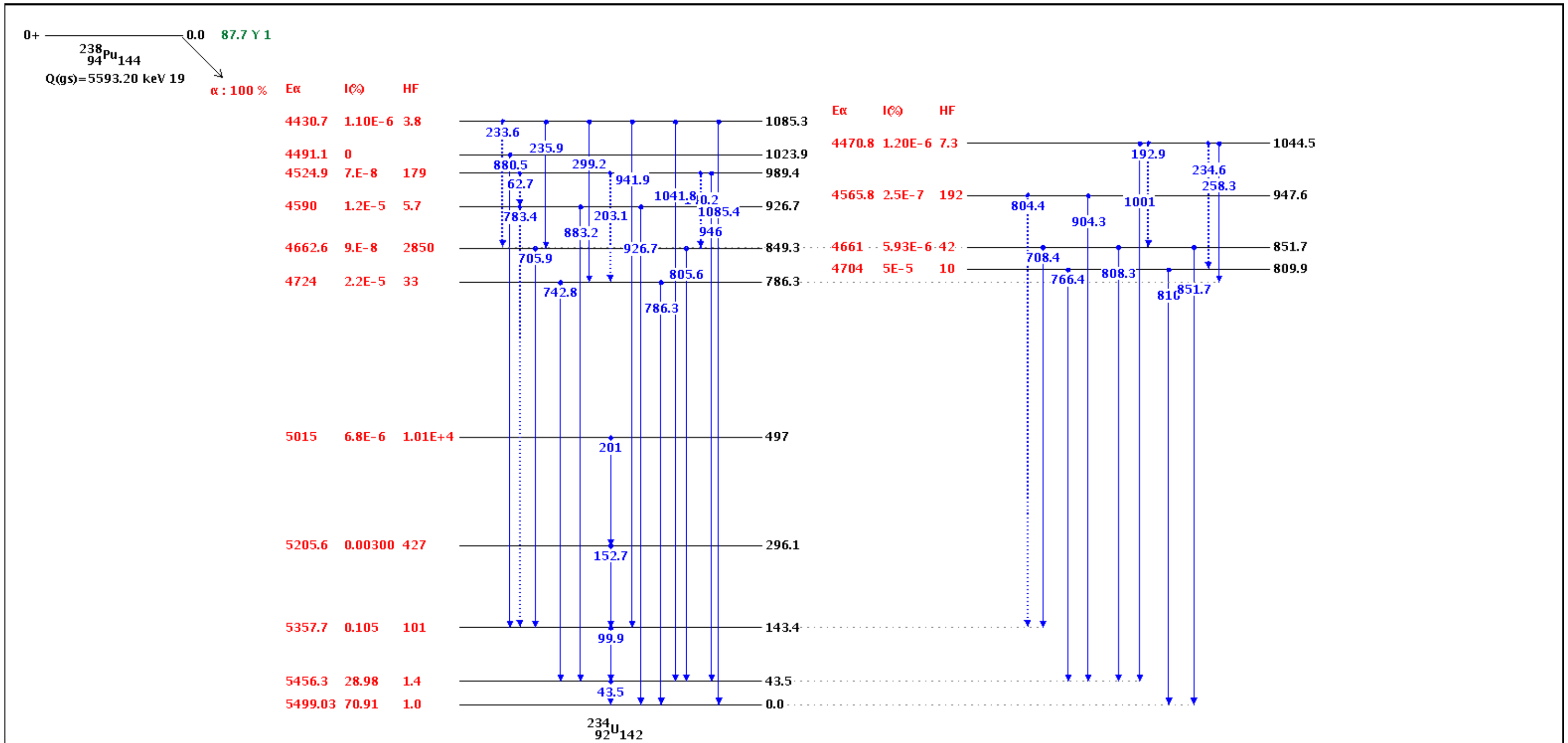

Figure 42: ^{238}Pu decay scheme.

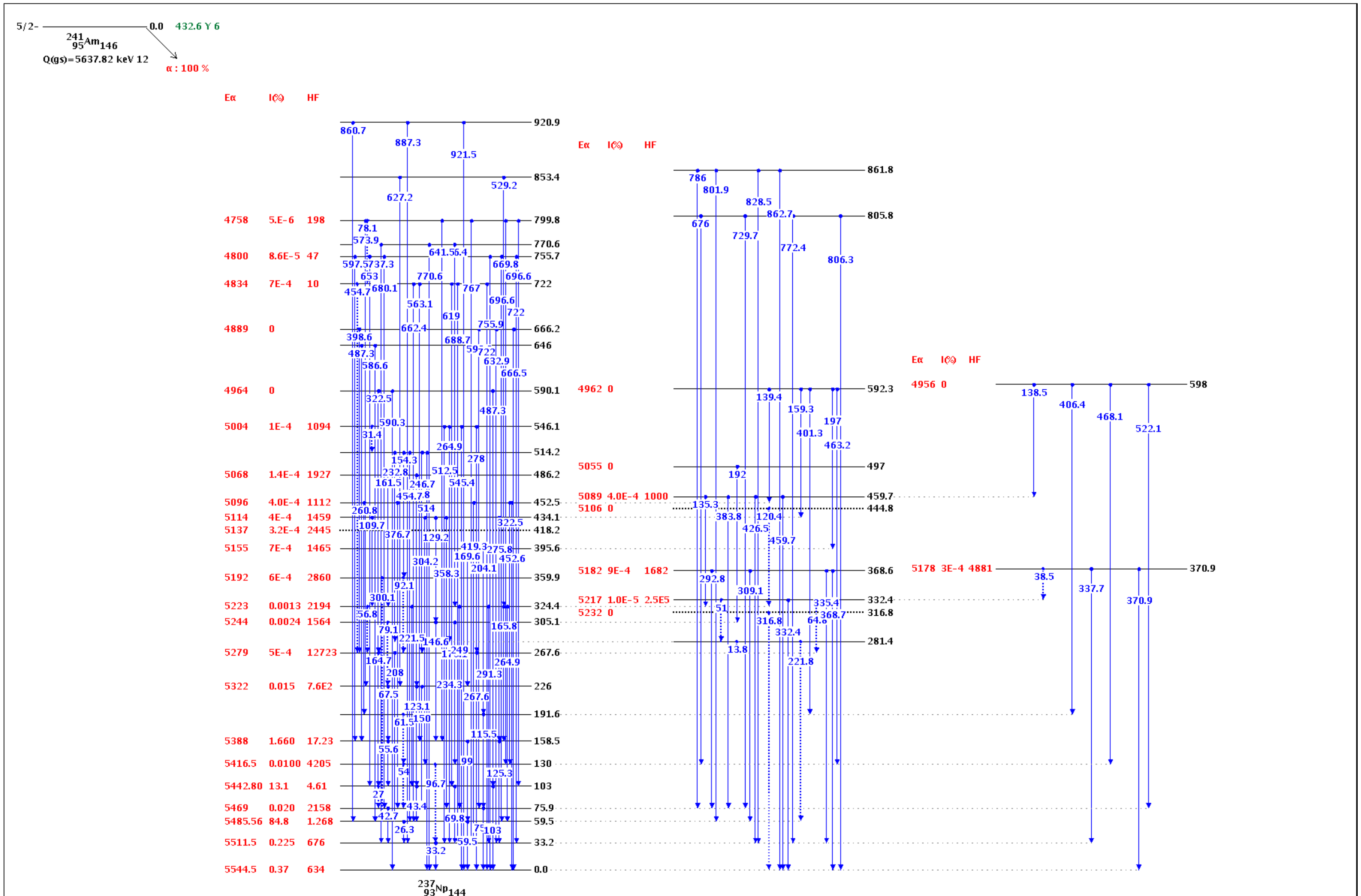

Figure 43: ^{241}Am decay scheme.

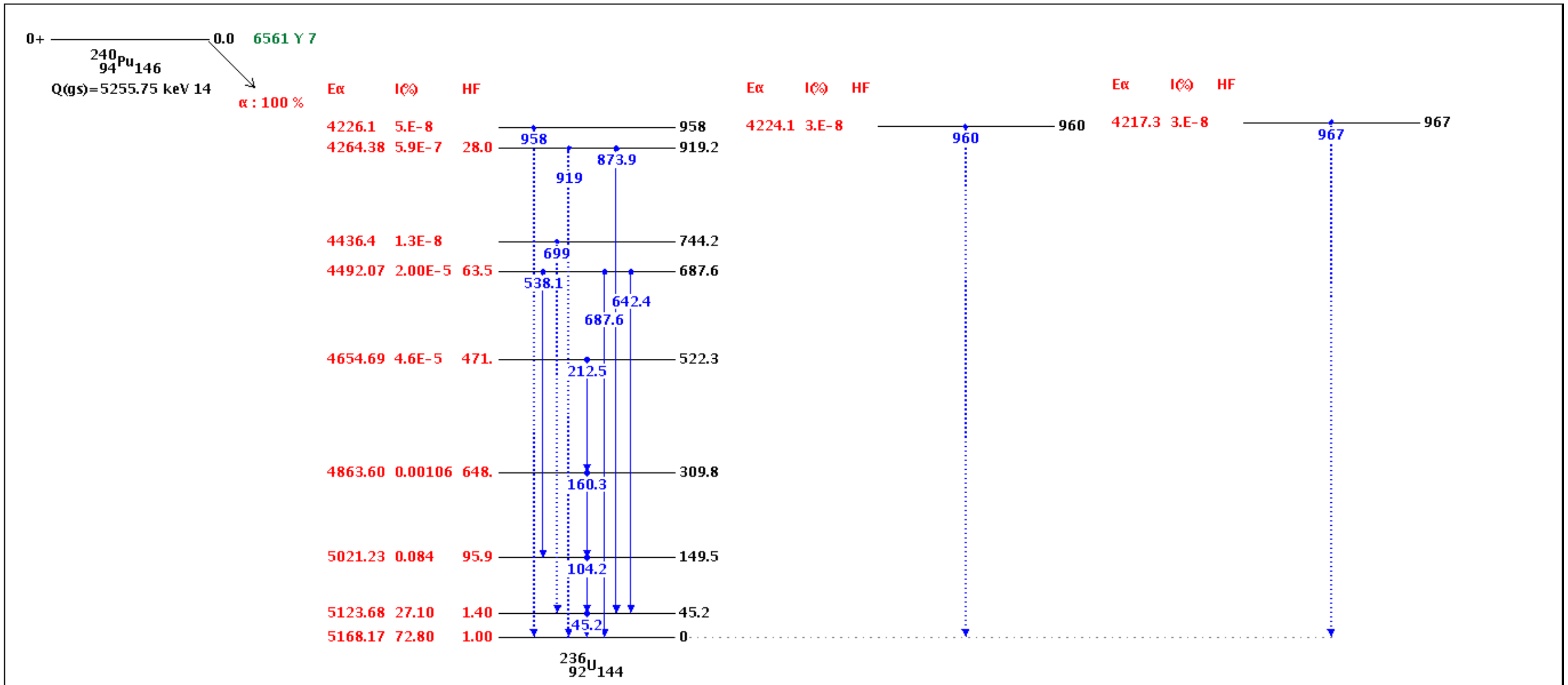

Figure 44: ^{240}Pu decay scheme.

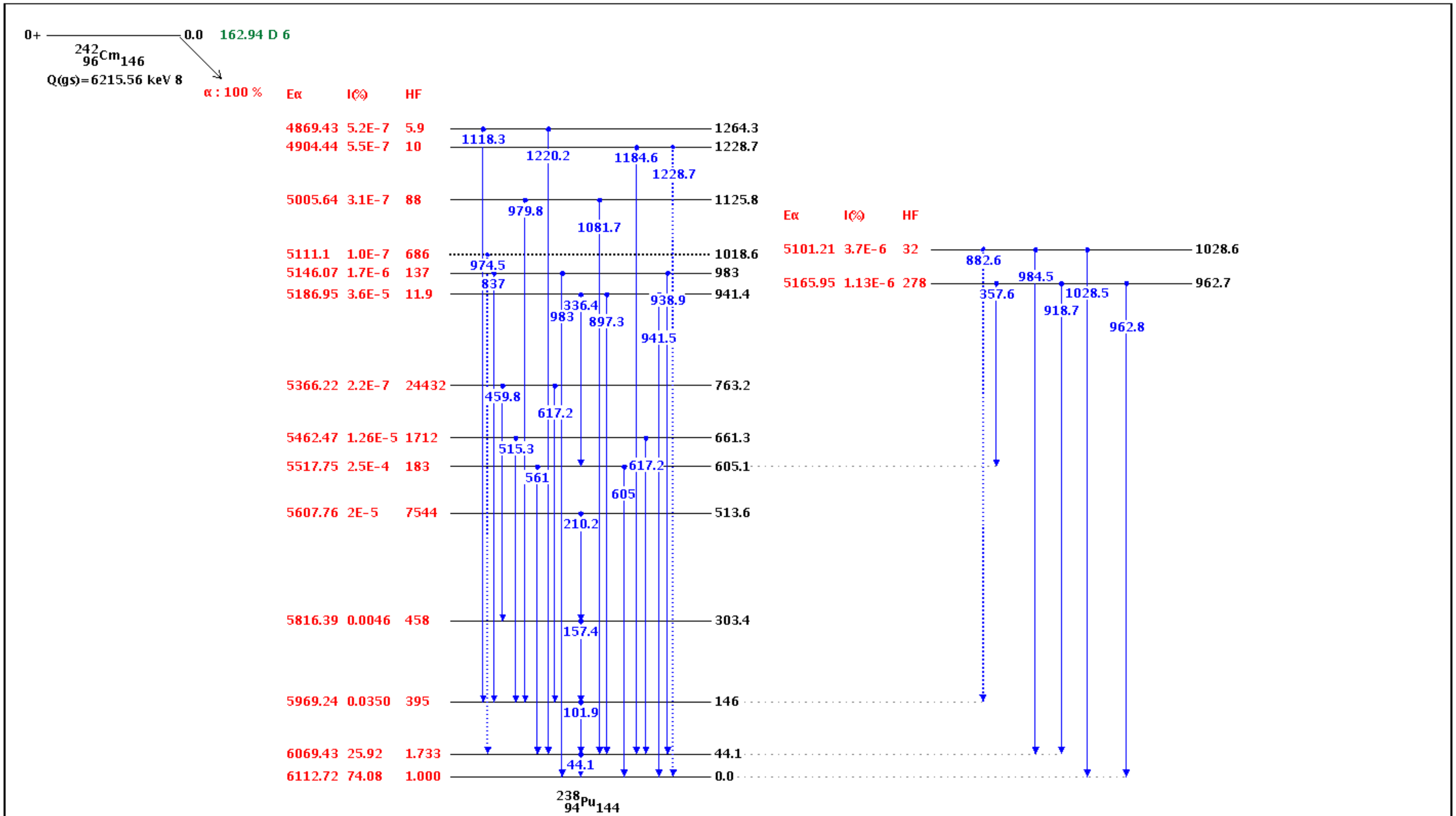

Figure 45: ^{242}Cm decay scheme.

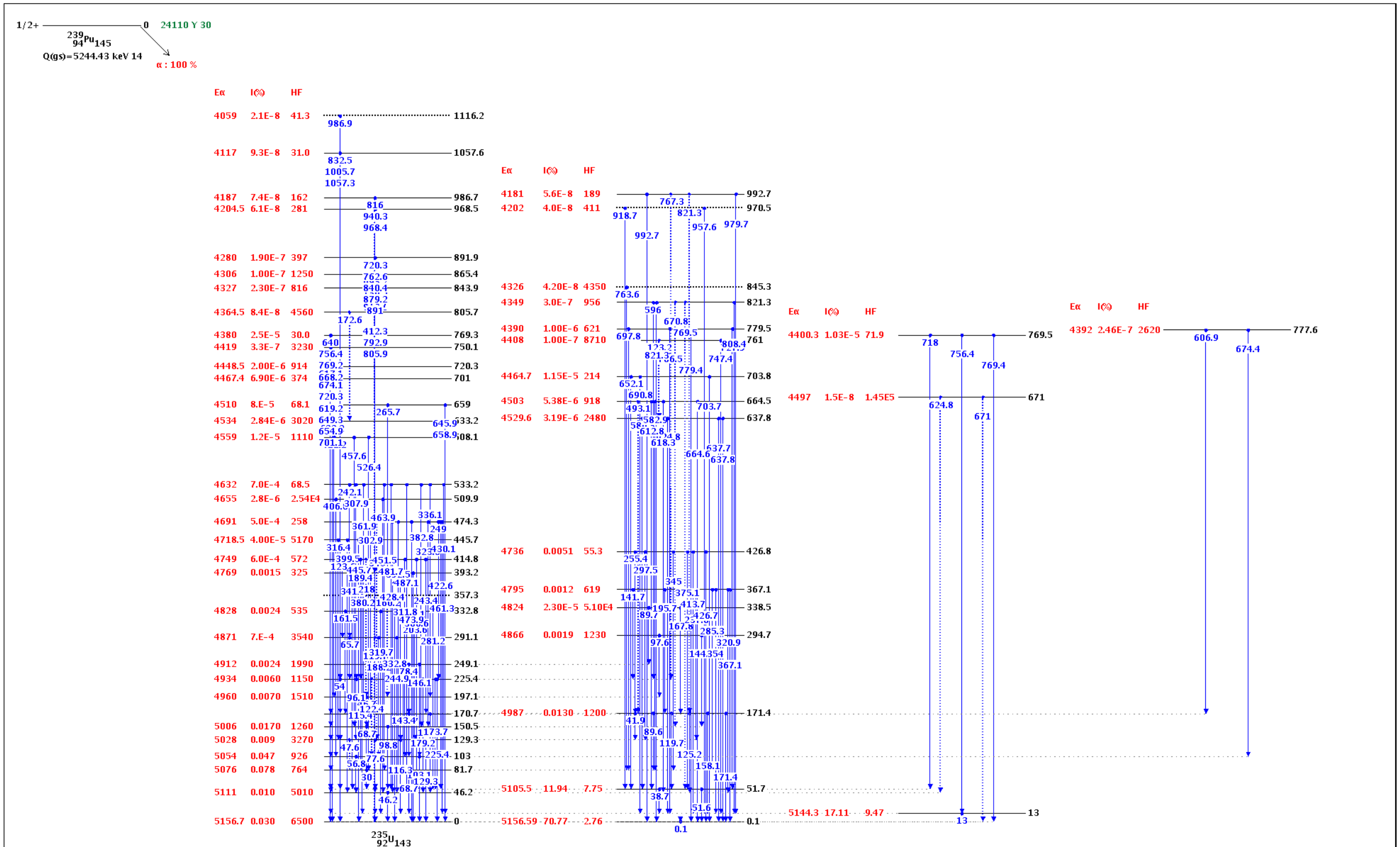

Figure 46: ^{239}Pu decay scheme.

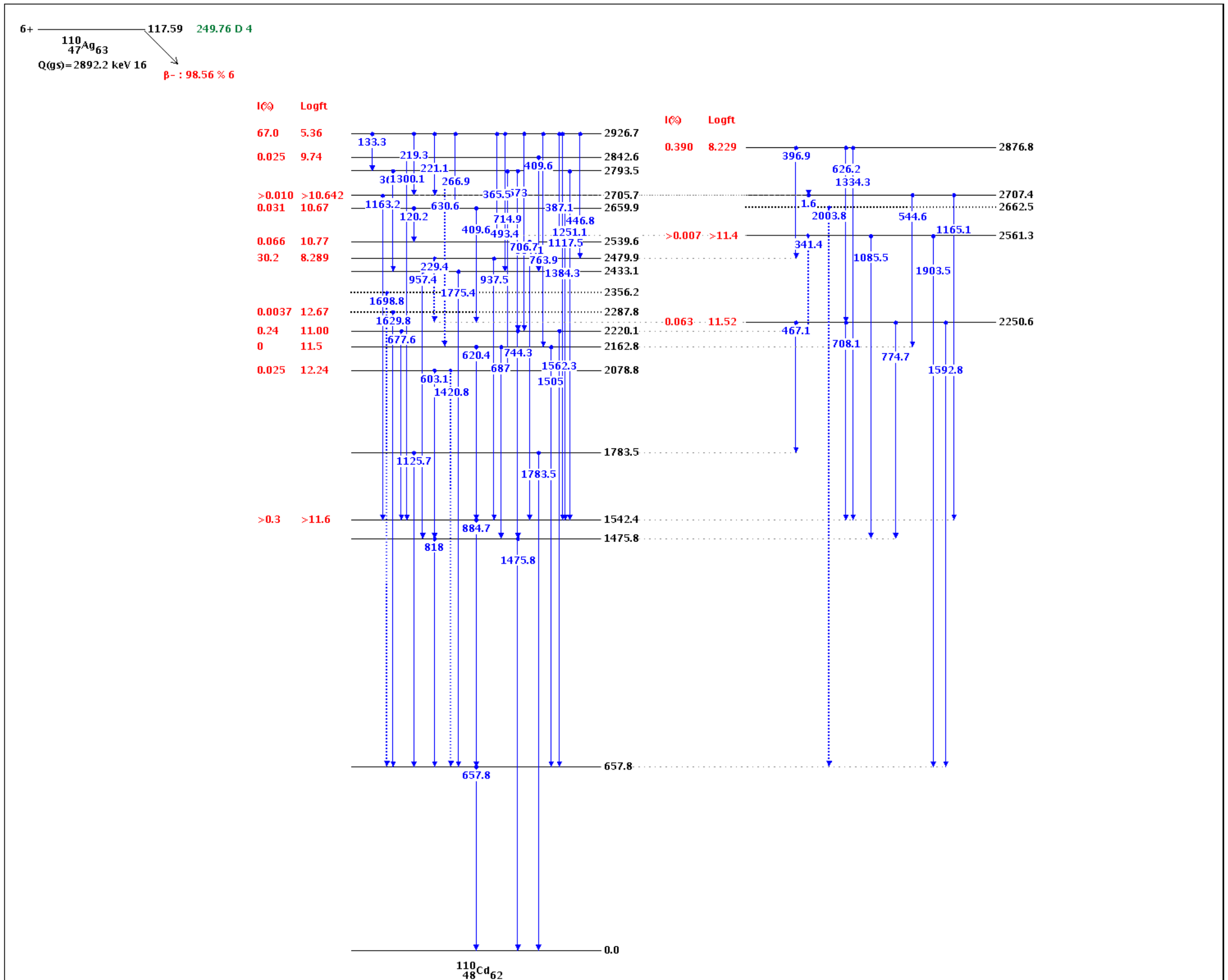

Figure 47: ^{110m}Ag decay schemes. ^{110m}Ag decays by both beta emission (98.56%, shown here) and isomeric transition (1.36%, shown in text).

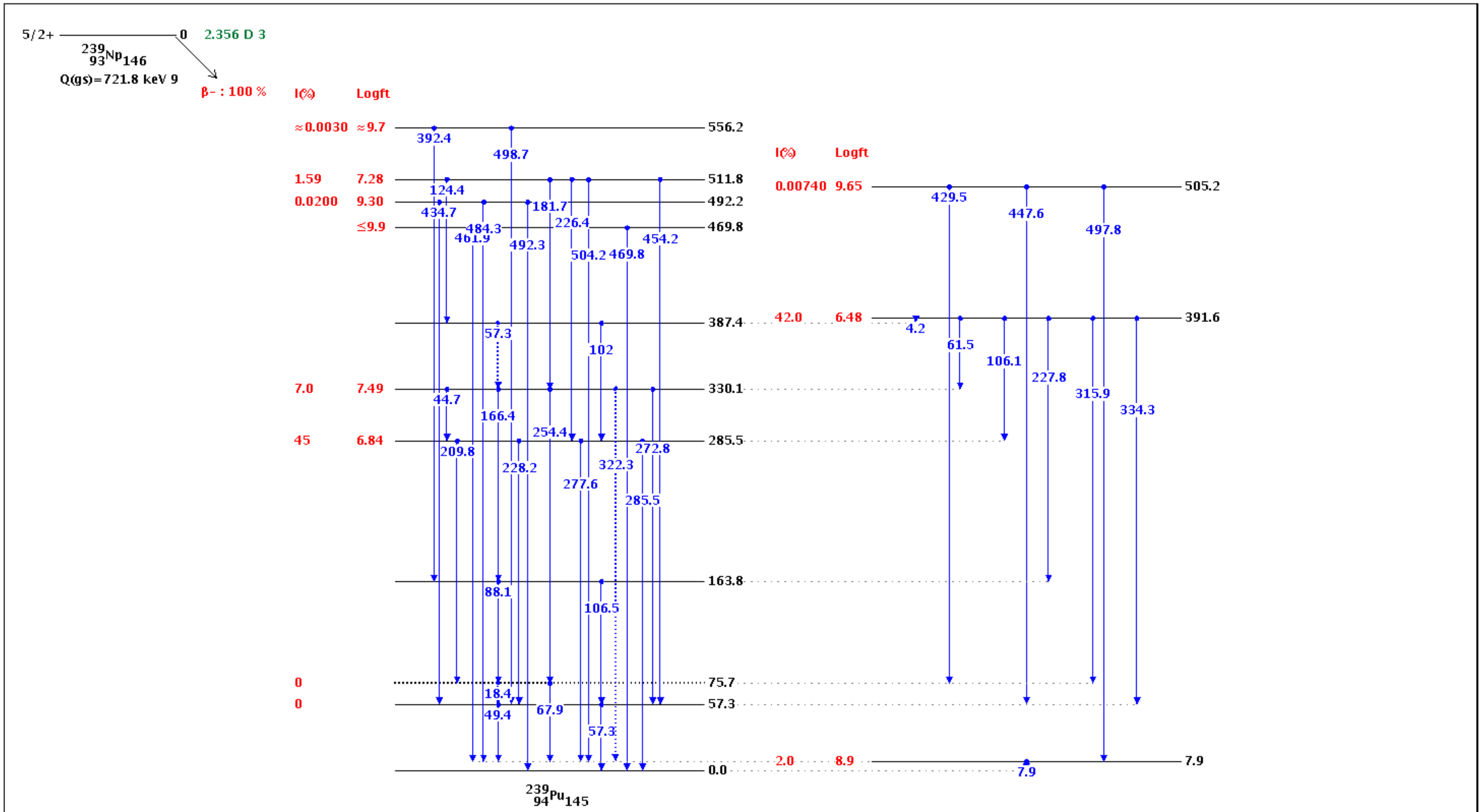

Figure 48: ^{239}Np decay scheme.

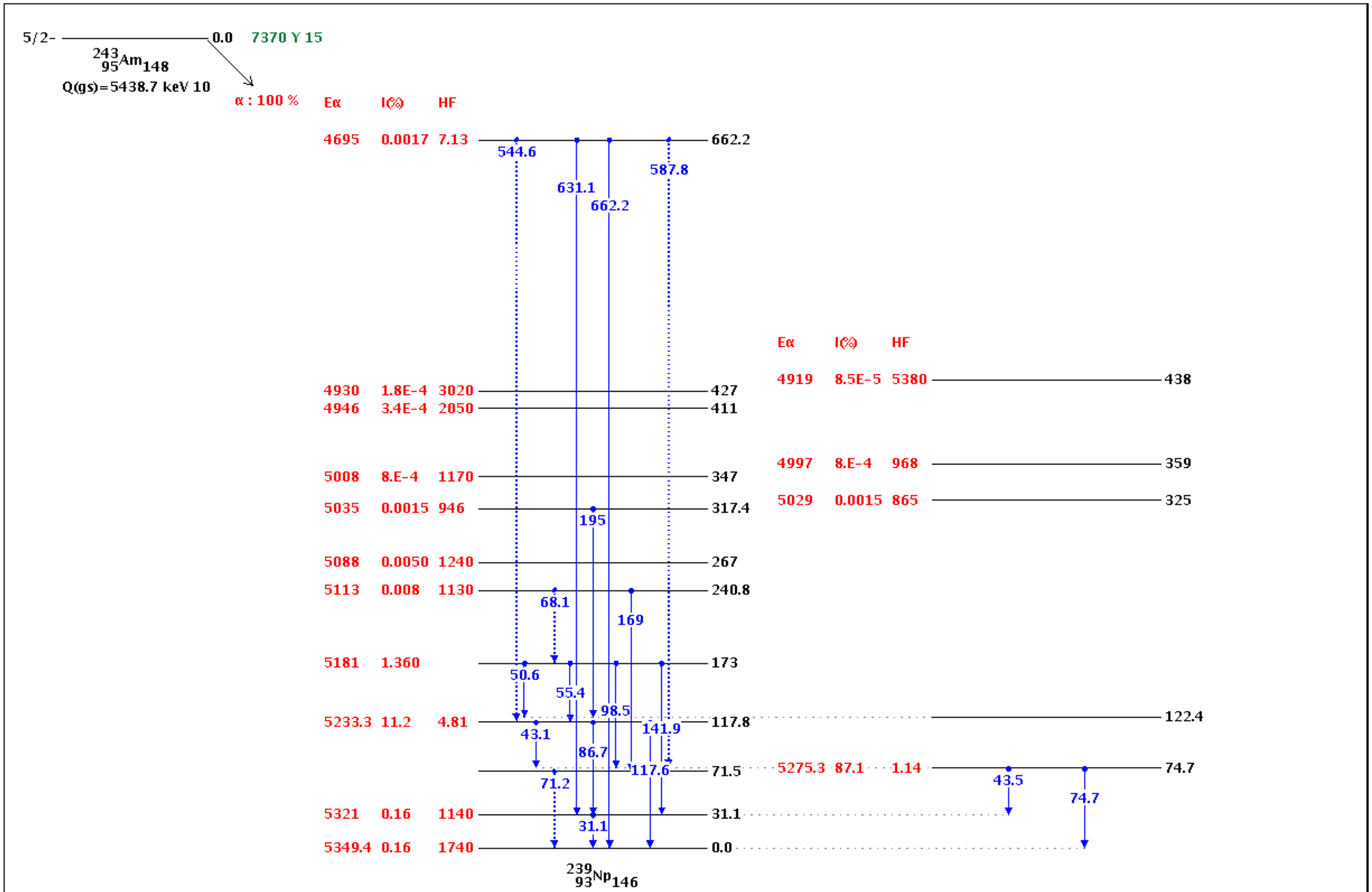

Figure 49: ^{243}Am decay scheme.

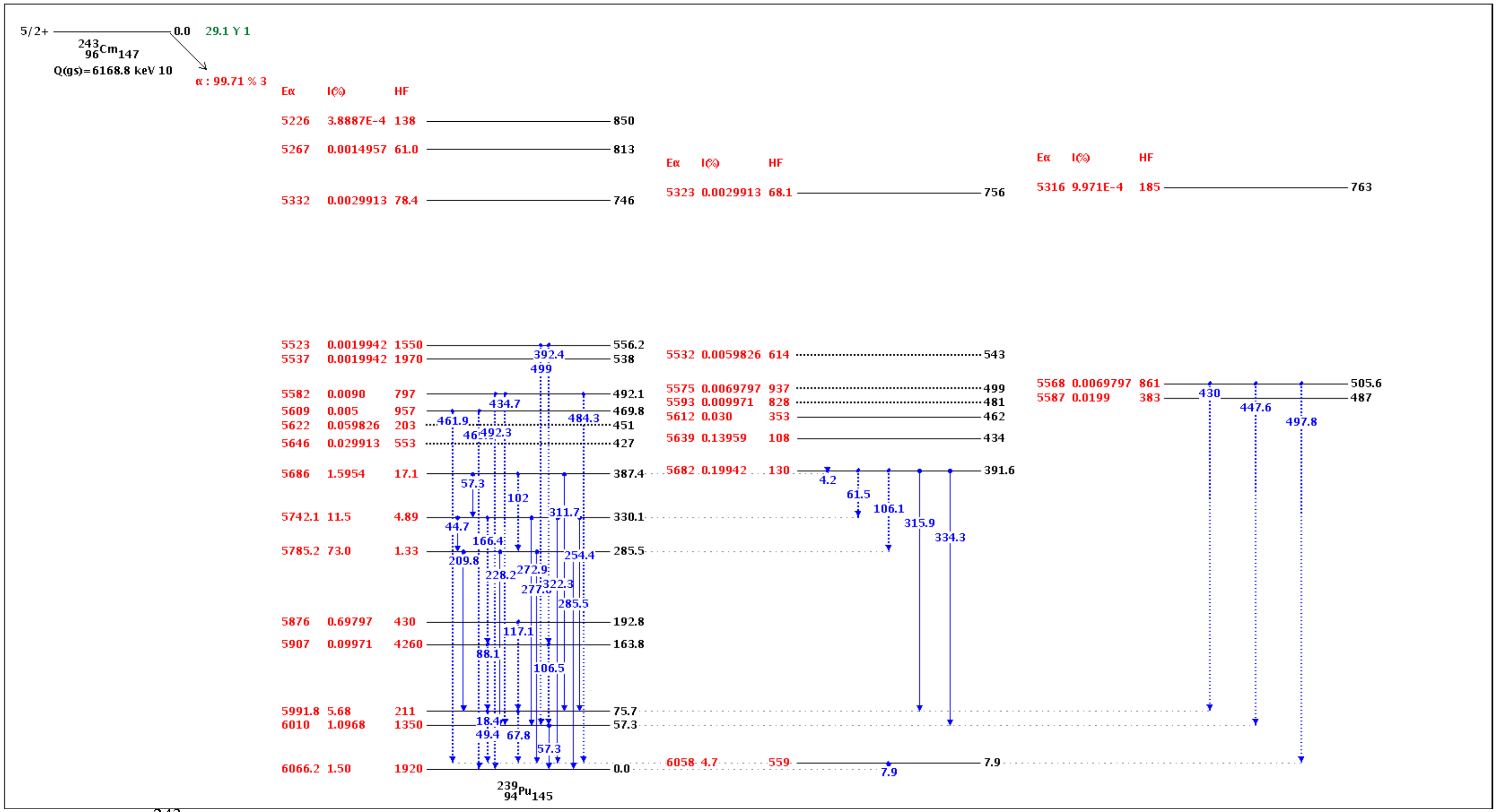

Figure 50: ^{243}Cm decay scheme.

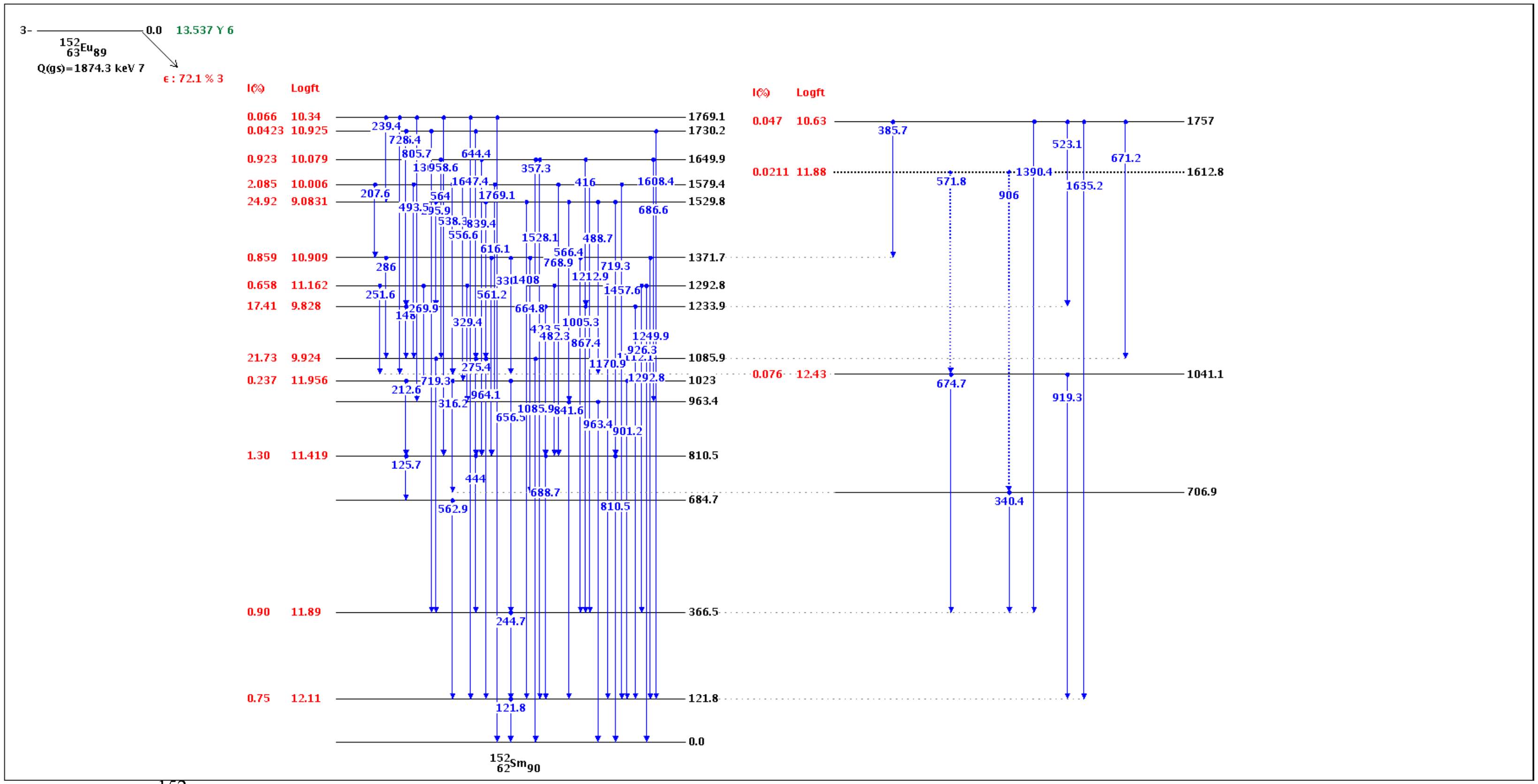

Figure 51: ^{152}Eu electron capture decay scheme.

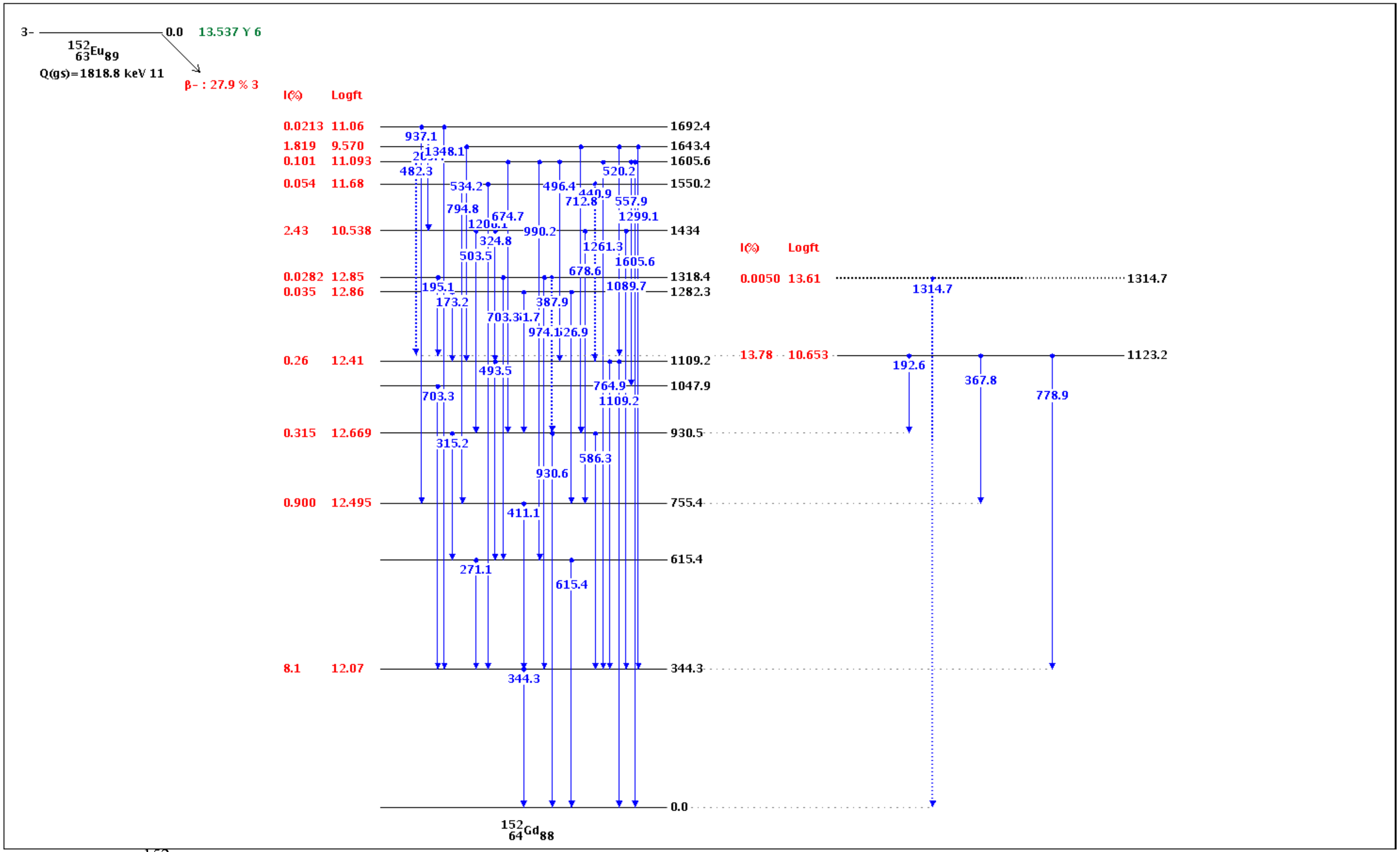

Figure 52: ^{152}Eu beta emission decay scheme.

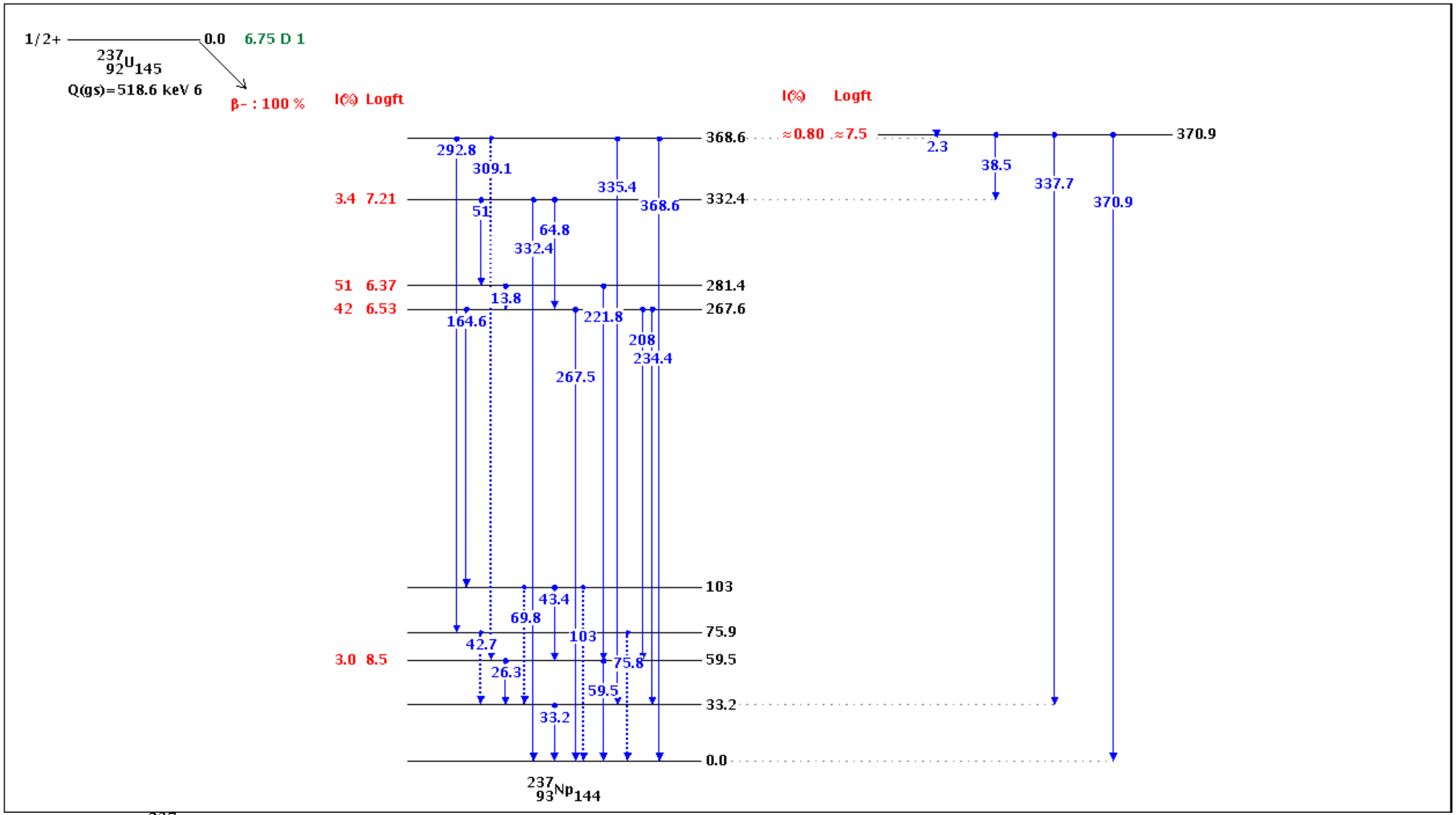

Figure 53: ^{237}U decay scheme.

Appendix 2: ORIGEN Input Example

The following is an example of an ORIGEN-S input file generated by ORIGEN-ARP for Combustion Engineering 14x14 fuel, 1 gram of Uranium at 4% ^{235}U enrichment, 45 MWd/kgU burnup, 32 MW/MTU average power, and a three year decay time. The power history consists of 3 cycles at 100% power up-time.

```
'This SCALE input file was generated by
'OrigenArp Version  6.0.13.12 January 12, 2010
=arp
ce14x14
4
3
468.75
468.75
468.75
32
32
32
1
1
1
0.7332
ft33f001
end
#origens
0$$ a4 33 a11 71 e t
ce14x14
3$$ 33 a3 1 27 a16 2 a33 18 e t
35$$ 0 t
56$$ 10 10 a6 3 a10 0 a13 4 a15 3 a18 1 e
57** 0 a3 1e-05 0.3333333 e
95$$ 0 t
Cycle 1 -2011.01.30 - CE14 - 45MWd
1e-006 MTU
58** 3.2e-05 3.2e-05 3.2e-05 3.2e-05 3.2e-05 3.2e-05 3.2e-05 3.2e-05
 3.2e-05 3.2e-05
60** 46.875 93.75 140.625 187.5 234.375 281.25 328.125 375 421.875
 468.75
```

```
66$$ a1 2 a5 2 a9 2 e
73$$ 922340 922350 922360 922380
74** 0.000356 0.04 0.000184 0.95946
75$$ 2 2 2 2
t
ce14x14
3$$ 33 a3 2 27 a33 18 e t
35$$ 0 t
56$$ 10 10 a6 3 a10 10 a15 3 a18 1 e
57** 468.75 a3 1e-05 0.3333333 e
95$$ 0 t
Cycle 2 -2011.01.30 - CE14 - 45MWd
1e-006 MTU
58** 3.2e-05 3.2e-05 3.2e-05 3.2e-05 3.2e-05 3.2e-05 3.2e-05 3.2e-05
 3.2e-05 3.2e-05
60** 515.625 562.5 609.375 656.25 703.125 750 796.875 843.75 890.625
 937.5
66$$ a1 2 a5 2 a9 2 e t
ce14x14
3$$ 33 a3 3 27 a33 18 e t
35$$ 0 t
56$$ 10 10 a10 10 a15 3 a18 1 e
57** 937.5 a3 1e-05 0.3333333 e
95$$ 0 t
Cycle 3 -2011.01.30 - CE14 - 45MWd
1e-006 MTU
58** 3.2e-05 3.2e-05 3.2e-05 3.2e-05 3.2e-05 3.2e-05 3.2e-05 3.2e-05
 3.2e-05 3.2e-05
60** 984.375 1031.25 1078.125 1125 1171.875 1218.75 1265.625 1312.5
 1359.375 1406.25
66$$ a1 2 a5 2 a9 2 e t
54$$ a8 1 a11 0  e
56$$ a2 8 a6 1 a10 10 a14 5 a15 3 a17 2 e
57** 0 a3 1e-05 e
95$$ 0 t
Cycle 3 Down - 2011.01.30 - CE14 - 45MWd
1e-006 MTU
60** 0.001 0.003 0.01 0.03 0.1 0.3 1 3
61** f0.05
65$$
'Gram-Atoms   Grams   Curies   Watts-All   Watts-Gamma
 3z   1   0   0   3z   3z   3z   6z
 3z   1   0   0   3z   3z   3z   6z
```

```
 3z   1   0   0   3z   3z   3z   6z
81$$ 2 0 26 1 a7 200 e
82$$ 2 2 2 2 2 2 2 2 e
83**
 1.0000000e+07 8.0000000e+06 6.5000000e+06 5.0000000e+06 4.0000000e+06
 3.0000000e+06 2.5000000e+06 2.0000000e+06 1.6600000e+06 1.3300000e+06
 1.0000000e+06 8.0000000e+05 6.0000000e+05 4.0000000e+05 3.0000000e+05
 2.0000000e+05 1.0000000e+05 5.0000000e+04 1.0000000e+04 e
84**
 2.0000000e+07 6.4340000e+06 3.0000000e+06 1.8500000e+06
 1.4000000e+06 9.0000000e+05 4.0000000e+05 1.0000000e+05 1.7000000e+04
 3.0000000e+03 5.5000000e+02 1.0000000e+02 3.0000000e+01 1.0000000e+01
 3.0499900e+00 1.7700000e+00 1.2999900e+00 1.1299900e+00 1.0000000e+00
 8.0000000e-01 4.0000000e-01 3.2500000e-01 2.2500000e-01 9.9999850e-02
 5.0000000e-02 3.0000000e-02 9.9999980e-03 1.0000000e-05 e
t
56$$ 0 0 a10  1 e t
56$$ 0 0 a10  2 e t
56$$ 0 0 a10  3 e t
56$$ 0 0 a10  4 e t
56$$ 0 0 a10  5 e t
56$$ 0 0 a10  6 e t
56$$ 0 0 a10  7 e t
56$$ 0 0 a10  8 e t
56$$ f0 t
end
=opus
LIBUNIT=33
TYPARAMS=NUCLIDES
UNITS=CURIES
LIBTYPE=ALL
TIME=YEARS
NPOSITION=1 2 3 4 5 6 7 8 end
NRANK=200
end
#shell
copy ft71f001 "C:\Users\Administrator\Desktop\Report\ORIGEN\45000MWd\CE14 -
45MWd\2011.01.30 - CE14 - 45MWd.f71"
del ft71f001
end
```

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